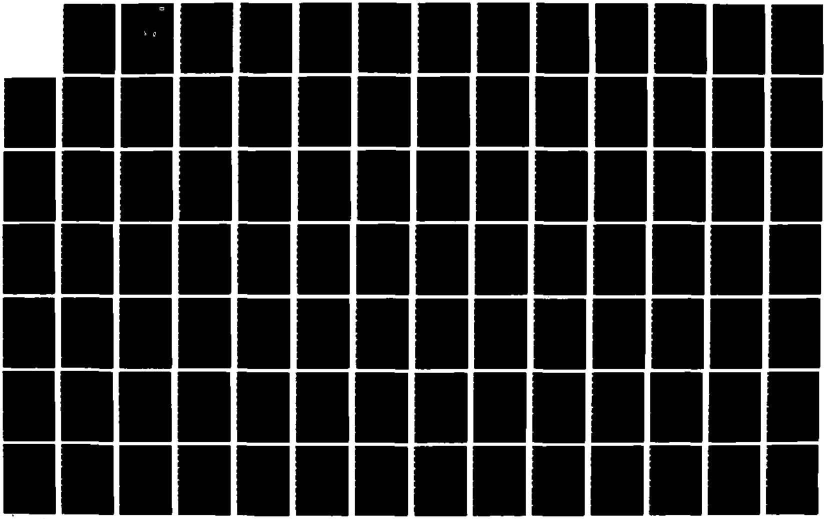
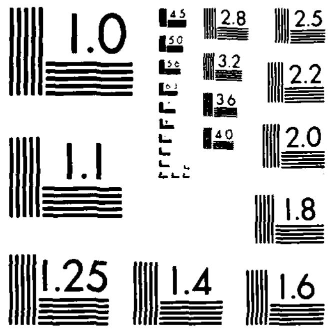
AD-A184 163 EMBANKMENT DAMS ON PERMAFROST DESIGN AND PERFORMANCE 1/2
SUMMARY BIBLIOGRAPHY (U) COLD REGIONS RESEARCH AND
ENGINEERING LAB HANOVER NH F H SAYLES JUL 87
UNCLASSIFIED CRREL-SR-87-11 F/G 13/2 NL





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Special Report 87-11

July 1987

US Army Corps
of Engineers
Cold Regions Research &
Engineering Laboratory

Embankment dams on permafrost
Design and performance summary, bibliography and an annotated bibliography

Francis H. Sayles

AD-A184 163

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

AD-A184163

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp Date Jun 30, 1986

1a REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY 2b DECLASSIFICATION / DOWNGRADING SCHEDULE	3 DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release, distribution is unlimited.
4 PERFORMING ORGANIZATION REPORT NUMBER(S) Special Report 87-11	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION U.S. Army Cold Regions Research and Engineering Laboratory 6b OFFICE SYMBOL (If applicable) CECERL	7a NAME OF MONITORING ORGANIZATION Office of the Chief of Engineers
6c ADDRESS (City, State, and ZIP Code) 72 Lyme Road Hanover, New Hampshire 03755-1290	7b ADDRESS (City, State, and ZIP Code) Washington, D.C. 20314
8a NAME OF FUNDING / SPONSORING ORGANIZATION 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER CWIS 31711
8c ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO / TASK NO / WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification)
Embankment Dams on Permafrost: Design and Performance Summary, Bibliography and An Annotated Bibliography

12 PERSONAL AUTHOR(S)
Francis H. Sayles

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
	FROM ______ TO ______	July 1987	114

16 SUPPLEMENTARY NOTATION

17 COSATI CODES

FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Construction	Design	Outlet structures	Reservoir shores
Dams	Embankment dams	Permafrost	Seepage
Deformation	Hydroelectric	Ponding	Spillways

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The designs of embankment dams on permafrost can be divided into two general types, frozen and thawed. The frozen type of embankments and their foundations are maintained frozen during the life of the structure. The thawed type of embankments usually are designed assuming that the embankment will remain unfrozen and its permafrost foundation will thaw during construction or during the operation of the structure. In some locations where water is to be retained intermittently for short periods of time, thawed embankments have been designed assuming the permafrost will remain frozen throughout the life of the embankment. In selecting this type of design for a particular site, many factors that are peculiar to cold regions must be considered. This summary of methods of design, construction and operation of embankment dams in permafrost areas records the successes and some failures that have occurred. Embankment dams have been built and successfully operated in Canada, Greenland, the USSR and Alaska. A number of failures have been reported in the USSR and one in Alaska. Most of the difficulties arose because insufficient attention was given to establishing and maintaining a reliable frozen condition and to controlling seepage. Often the thawing and seepage in a frozen embankment or foundation are initiated

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL Francis H. Sayles	22b TELEPHONE (Include Area Code) (603) 646-4100 22c OFFICE SYMBOL CECERL-EC

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

18. Subject Terms (cont'd). Stability
Tailing dams
Thermal regimes

19. Abstract (cont'd).

adjacent to the spillway or outlet works indicating that inadequate cooling or impervious seepage cutoffs were established at these points. Further research is needed to improve embankment design in permafrost.

PREFACE

This report was prepared by Francis H. Sayles, Research Civil Engineer, Geotechnical Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. This work was funded by the Directorate of Civil Works, the Office of the Chief of Engineers, under Civil Works Order No. CWIS 31711, Time Rate and Magnitude of Degradation of Permafrost.

The author gratefully acknowledges the critical reviews of the report by Thaddeus C. Johnson, Chief of the Civil Engineering Research Branch and William F. Quinn, Chief of the Geotechnical Research Branch. Their constructive suggestions are appreciated.

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EMBANKMENT DAMS ON PERMAFROST: DESIGN AND PERFORMANCE SUMMARY, BIBLIOGRAPHY AND AN ANNOTATED BIBLIOGRAPHY

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SECTION I

INTRODUCTION

The design, construction and operation of embankment dams in the Arctic and Subarctic present unique problems that are related to freezing temperatures and the special geological and climatic conditions of the cold regions. Because of the relatively limited experience with embankment dams on permafrost it is important to take advantage of the technical information that is available. Therefore this report was prepared to acquaint the reader with the information that is available and thus benefit from the experiences of others.

The objectives of this literature survey was to: summarize briefly the existing state-of-the-art on this subject, Section II; assemble an extensive list of references covering the subject of embankment dams on permafrost, Section III; and collect pertinent information on methods of analysis, design approaches, construction techniques, and procedures used to operate dams successfully on permfrost, Section IV. The last objective is accomplished by means of an annotated bibliography which includes case studies of specific projects. Of the 27 references in the Bibliography, 228 are contributions from the Soviet Union, 15 from Canada and 27 from the United States. Although much of the Soviet literature is repetitive, it clearly indicates that the USSR has had the widest variety of experience with embankment dams on permafrost and they have devoted much research to this subject.

Fifty-nine entries are presented in the <u>Annotated Bibliography</u>. All of the annotations are based on the original papers or English translations of the Soviet papers. These annotations are condensations of portions of

the papers that are pertinent to the design, construction and operation of the respective embankment dam structure and reservoir, with a minimum of attention given to environmental or related effects. The entries are listed alphabetically by first author in the Bibliography and Annotated Bibliography sections of the report. Where two or more papers are by the same author, the listing is chronological, beginning with the latest paper.

To assist the reader who is interested in a reference list for one of the general topics under embankment dams on permafrost, authors are listed alphabetically in the section List of Authors by Subject, Section IV, under the following subject headings:

Design and Construction
Instrumentation
Outlet Structures
Reservoir Shores
Seepage
Stability and Deformation
Tailing Dams
Thermal Regime

It should be noted that an asterisk (*) preceding an entry in the Bibliography or the List of Authors by Subject indicates that an annotated entry appears in the Annotated Bibliography.

SECTION II

DESIGN AND PERFORMANCE

To date, the water-retaining structures constructed and maintained on permafrost in North America have been designed and built using a combination of soil mechanics principles for unfrozen soils and permafrost theory. In the USSR, at least five sizeable hydroelectric and water supply embankment dams as well as several small water supply embankment dams have been constructed and maintained on permafrost. The larger dams are understood to have performed well, but the smaller dams have been a mix of successes and failures. (See Table 1 for examples of problems recorded in the literature.) Specific criteria are still lacking for design, operation, and post-construction monitoring of water-retaining embankments founded on permafrost. The purpose of this review is to examine the current practice, point out how it is deficient, and note what major problems need attention.

CURRENT PRACTICE

General considerations

In current practice, the designs of water-retaining embankments on permafrost can be divided into two general types, frozen and thawed. The frozen type of embankments and their foundations are maintained frozen during the life of the structure. The thawed type of embankments usually are designed assuming that the embankment will remain unfrozen and its permafrost foundation will thaw during either the construction or the operation of the structure. In some locations where water is to be retained intermittently for short periods of time, thawed embankments have been designed assuming the permafrost is to remain frozen throughout the life of the embankment. In selecting the type of design for a particular site, many factors that are peculiar to cold regions must be considered, including:

- The anticipated type of service of the embankment; i.e. retain water continuously or only intermittently.

Table 1. Problems recorded for embankment dams on permafrost.

River Name	Location	Embankment Type	Height (m)	Length (m)	Problem Description	Reference
					Thawing and Seepage at Spillway and Outlet Works	
Unknown	Northern USSR	Compact earth	21.4	230	Municipal water supply dam was completed in 1967. In 1970, a breach occurred through embankment at supply intake pipes due to thermal erosion and seepage.	Anisimov & Sorokin (1975)
Hess Creek	Livengood, AK	Hydraulic & compacted earth fill	24	488	Completed in 1946 for water supply in mining operations. In 1962 breached between spillway due to thermal erosion and seepage.	Rice & Simoni (1963)
Myla River	Zarechnyy Region, USSR	Compact frozen sand		-	Constructed of uncompacted frozen sand during winter. Seepage through earth dam and joints in wooden spillway caused thawing and failure of dam in 1954.	Lyskanov (1964)
Vilyuy River (Dam II)	USSR	Embankment w/crib cutoff, w/sand and silt	12	300	Constructed 1957-1960 on permafrost. During initial operating period, large seepage volume occurred and spillway was completely destroyed in first flood. After reconstruction in 1969, leakage was observed from the reservoir through caverns in foundation of the dam and at contact points with the spillway. Causes of problems: (1) spillway too small for flood, (2) ice-retaining structures not located far enough upstream from dam, (3) poor spillway construction, (4) fissures in foundations not sealed, (5) poorly compacted runoff.	Biyanov (1966)

Table 1 (cont'd).

River Name	Location	Embankment Type	Height (m)	Length (m)	Problem Description	Reference
Vilyuy River (Dam III)	USSR	Embankment with core	3	-	Clay-ice core constructed in winter with frozen clay and water. Seepage along spillway; contact between it and the embankment resulted in degradation of frozen core, which soon became non-functional.	Biyanov (1966)
					Thermal Regime of Embankment and Foundation Not Maintained	
Dolgala River	Noril'sk, USSR	Refrigerated earth	10	130	Constructed in 1942 with a "clay-concrete" (probably cement-stabilized clay) core with two rows of freezing pipes parallel to dam axis. The core was to reduce seepage during the freezing period. Calcium chloride brine, circulated through the freezing pipes, was not cooled sufficiently by atmosphere. Furthermore, the brine leaked into the dam, causing melting of embankment. Snow deposits impeded freezing from the downstream face. Disaster was averted by converting the cooling brine to air and running the circulating system only when air temperatures were colder than the ground. Only after an ice sheet was created on the downstream face by water applications in the winter was thermal regime stabilized throughout the year.	Tsvetkova (1960), Borisov & Shamshura (1959)
Sredniy El'gen River	Kolyma River Basin, USSR	Earth	7.4	300	Built in 1944. Large deformations and cracks occurred along dam due to seepage and thawing. Seepage developed where timber piling was used as a cutoff. To prevent failure, an upstream blanket was constructed.	Tsvetkova (1960)

Table 1 (cont'd). Problems recorded for embankment dams on permafrost.

River Name	Location	Embankment Type	Height (m)	Length (m)	Problem Description	Reference
Myaundzha River	Kolyma Basin, USSR	Earth fill w/core	8	860	In 1952, initial attempts made to construct dam in the winter to obtain a frozen embankment, but summer thawing in the summer required artificial cooling. This was accomplished by installing "freeze" pipe in the embankment and circulating cold air down the pipes. The abutments were not protected by freeze pipes, thawing occurred at these locations, and the seepage ensued. (This article, in 1957, implied impending disaster).	Tsvetkova (1960)
Amozar River	Near Mogocha on the Amur Railroad, USSR	Crib-core Rock-earth fill	4	-	Failed due to seepage and thawing through body of the embankment. (Apparently built in 1910-1916.)	Tsvetkova (1960)
Kvadratnyy	Noril'sk, USSR	Compact earth fill	6	-	Dam used for cooling water supply for electric power station. Destroyed within 1 yr after construction by thawing of foundations and abutment soils.	Borisov & Shamshura (1959)
Stake 89 (Picket Creek)	Noril'sk, USSR	Compact earth fill	5.5	-	Destroyed within 2 yrs after construction when seepage through the unfrozen soil thawed the frozen soil.	Tsvetkova (1960)
			Inadequate Construction Procedures			
Pravaya Magdagacha River	Northern USSR	Compact earth with concrete diaphragm	7.3	-	Failed after 2 yrs of operation. Large deformation of dam resulted in cracks in the diaphragm all along the embankment dam and at the junction of the weir. Final failure occurred during heavy thunder storm when leakage appeared at the crest. Failure occurred over a 65-m length.	Tsvetkova (1960), Saverenskii (1950)

Table 1 (cont'd).

River Name	Location	Embankment Type	Height (m)	Length (m)	Problem Description	Reference
Mykyrt River	City of Petrovsk-Zabaykalskiy, USSR	Earth	9.5	-	Built in 1792. In attempting to repair the wooden spillway of the 137-yr-old dam, proper measures were not taken to preserve the frozen embankment. The dam had to be completely rebuilt in 1945.	Tsvetkova (1960)
Bol'shoy Never River	Skovorodino, USSR	Earth silt and gravel with clay core	9.6	530	Built in 1932. The clay-ice core became semi-liquid and the stability of the dam was threatened. In 1934 ballast was applied to the slopes, wooden piling was driven, soil behind the piling was replaced by more impervious material, and a wood gallery was constructed to catch the seepage. Deep thawing of foundation soil and bedrock in 1936 did not cause serious problems.	Tsvetkova (1960)
Vilyuy River (Dam V)	USSR	Random earth fill with timber	16.8	332	Constructed on ice-saturated clayey silt and disintegrated rock overlying fissured clay-limestone. In the springs of 1965 and 1966 boils appeared downstream of the dam. Seepage was caused by thawing of ice in rock fissures during construction.	Biyanov (1966)

- The width, depth, temperature, and chemical composition of the body of water to be retained by the embankment.

- Regional and local climate conditions, especially temperature.

- The temperature of the existing permafrost.

- The extent in area and depth of the permafrost.

- The availability of the type of earth materials required for construction.

- The accessibility of the construction site for logistics involving man-made construction materials.

- The consequences to life and property in the event of embankment failure.

- The effects of the construction and operation of the embankment and reservoir on the environment.

- The orientation of the downstream slope (i.e. the dry slope) of the embankment with respect to solar radiation.

- Frost action on the dry slopes and crest of the embankment.

- The economics of constructing a selected design in the cold region.

In addition to these rather general factors, each type of design has special requirements that must be taken into account in making the final selection of a particular design.

Unfrozen embankment on thawing permafrost

The design for an unfrozen embankment founded on thawing permafrost is most suitable for sites where the foundation materials are thaw-stable; i.e. where the thawing strengths of the earth materials provide an adequate factor of safety against shear failure, and deformations resulting from thawing will not endanger the integrity of the embankment. This requirement usually restricts the use of the thawing foundation design to sites where permafrost soil is ice-poor (i.e. free from segregated ice) or where reasonably sound bedrock can serve as the foundation and the permeability of the thawed foundation is tolerable. At sites where only a portion of the foundation contains ice-rich permafrost at shallow depths, this ice-rich portion is usually thawed before placing the embankment, or the frozen soil is excavated to a predetermined depth (Gluskin and Ziskovich, 1973) and replaced. MacPherson et al. (1970) suggest a method of estimating the

depth of excavation so that thaw consolidation can be limited to a predetermined amount during the operation of the embankment.

Where the permafrost is not removed and the foundation is expected to thaw during the life of the structure, the embankment design is similar in many respects to that of a water retaining embankment located in a temperate climate when the effects of thawing on the consolidation, permeability and strength are taken into account. However, special consideration is given to certain elements of the embankment. One such element is the impervious zone, which must be constructed of self-healing soils (Gupta et al. 1973) so that this zone can remain "impervious" even if cracking occurs during the settlement of the foundation. Soils that become stiff and brittle when compacted in the impervious zone are avoided. Other design provisions that are often included to accommodate the anticipated settlement are: the use of flatter embankment slopes; overbuilding the height of the embankment by an amount equal to the anticipated settlement; and periodically rebuilding portions of the embankments that settle more than a tolerable limit (Johnston 1969, MacPherson et al. 1970). Prethawing followed by preloading to consolidate the foundation before placement of the embankments has also been suggested as a means of reducing foundation settlements (Gluskin and Ziskovich 1973). The concept of utilizing sand drains in a thawing foundation to increase the rate of consolidation and, hence, quickly improve the shear resistance and stability of embankments has been used successfully (Johnston 1965, 1969, MacPherson et al. 1970). In addition, analytical methods have been developed for estimating the rates of thaw and settlements of dikes on permafrost during operations using simple heat conduction and heat balance equations for a one-dimensional transient condition that takes into account heat from water seepage (Brown and Johnston 1970).

Grouting has been used successfully in cold regions to stabilize thawing foundations and to cut off seepage. At sites where the foundation material is expected to be weakened or where initial seepage is expected to present a problem when the ice melts from the voids, the foundation areas may be thawed and grouted before the embankments were constructed (Gluskin et al. 1974). As an alternative, the fissures or voids can be grouted in steps during the operational life of the embankment. In this case, the foundation is thawed by the heat from the impounded reservoir. As the

thawing front progresses into the foundation, the fissures and voids are grouted periodically (Demidov 1973). This method requires careful and continuous monitoring of the thawing front beneath the impervious zone of the embankment.

Essential elements of any thawed embankment are the filters and drainage systems for the safe control of seepage through and beneath the embankment. The design of these elements is similar to those for embankments in non-permafrost areas. However, special provisions are required to avoid plugging the drainage system with ice, which could render it useless at a time when it may be needed most.

Unfrozen embankment on non-thawing permafrost

The use of a thawed embankment on a non-thawing permafrost foundation is usually limited to regions of cold permafrost where the water is to be retained by the embankment for a relatively short period of time each year or less frequently. At these sites, artificial cooling of the foundation may be required during construction (Rice and Simoni 1963, Kitze and Simoni 1972) and maybe even during the operation period. As a further provision for keeping the foundation frozen, it is essential that a positive seepage cutoff be provided (Borisov and Shamshura 1959, Trupak 1970). Such a cutoff may take the form of sheet piling, a plastic membrane (Belikov et al. 1968), or other waterproof materials that are sealed to the frozen foundation and extend up to the embankment crest. The most economical and effective seepage cutoff often is a zone of frozen soil. This zone can be created from the surfaces of the embankment slopes during the winter season by natural freezing when water is not being retained. Effective temperature and water seepage monitoring systems are necessary in operating this type of water-retaining embankment in order to detect thawing that may occur that would initiate a seepage path through the embankment or in the foundation beneath it. Of course, if the frozen zone is to be maintained continuously, then the dam would be classified as a frozen embankment on permafrost which is discussed in the following paragraph.

Frozen embankment design

A frozen embankment design with preservation of a frozen foundation, is usually essential for sites where the foundation becomes unstable upon thawing to a considerable depth. This type of design provides a practical

approach for regions where the permafrost is continuous and at a low temperature. The most essential requirement of this type of design is that the frozen embankment and foundation be completely impervious to seepage, since heat from seeping water would eventually cause thawing. If left unchecked, the combination of thermal and mechanical erosion (piping) could breach the embankment.

Currently, frozen embankments operating with permanent reservoirs are located in regions where the mean annual temperature is -8°C or colder. Even at these temperatures, embankments 10 m or more in height require supplemental artificial refrigeration for at least part of each year to ensure that the embankment and foundation remain frozen. In addition to the climate at the site and the embankment height, the lateral dimensions of an impounded reservoir must be considered in a thermal analysis of the dam. With time, a reservoir develops a talik beneath it similar to that produced by a lake of similar dimensions. The larger the talik, the greater the risk of thawing under the embankment and of initiating seepage or stability difficulties.

It has been suggested that for a frozen embankment design almost any type of earth material can be used to construct the embankments, provided the pores of the material are filled with ice and the mass is maintained frozen during the life of the structure (Johnston and MacPherson 1981). It has also been suggested that ice be used as an impervious core (Tsytovich 1973). Although these suggestions have merit, they also could entail risk of difficulties. A large portion of the upstream section of an embankment that is required to retain a permanent reservoir, and the foundation supporting it, will thaw from the heat of the reservoir. Therefore, the upstream slope can become unstable if this portion of the embankment is not constructed of thaw-stable materials and if provisions are not made to accommodate the differential settlement that can occur between the core and the upstream shell.

Spillways and water outlet control structures founded in permafrost, whose frozen state must be preserved, require special considerations with respect to their location and to the preservation of permafrost (Tsytovich et al. 1972, Gluskin and Ziskovich 1973). When these facilities conduct water downstream near or through the embankment, the heat released into the structure by the flowing water can eventually melt the supporting perma-

frost, which may result in detrimental settlement of the structure and breaching of the seepage barrier. Table 1 reveals that most of the problems that have been associated with water-retaining embankments on permafrost have been related to seepage around and beneath outlet structures. To avoid these problems, spillways and other outlet structures usually are not located within or adjacent to ice-rich permafrost without special refrigeration or other measures to preserve the earth in a frozen state. Where possible, the outlet facilities are located at a remote site and preferably in competent bedrock. For small dams the use of siphons and pumps have been used to control reservoir levels (Gluskin and Ziskovich 1973). A chute spillway elevated above the embankment surface (Bogoslovskii et al. 1963) is one possible solution for discharging water from pumps or siphons without thawing the downstream slope of an embankment. The most common practice is to locate the spillway in one of the abutments founded on bedrock, and to use refrigeration or grout to control the seepage. The importance of a positive seepage cutoff must be emphasized because of the possible formation and enlargement of a talik that can grow laterally from the outlet works into and beneath the adjacent embankment. As a result, the entire facility can be endangered if it is a frozen-type design.

Thermal analysis

Essential to the design of water retaining embankments on permafrost is the determination of the thermal regime throughout the life of the structure (Bogoslovskii 1958, Tsytovich et al. 1972). A number of methods have been developed and others are being developed for estimating the thermal regimes of these embankments and their foundations. Some of the methods currently in use include:

a. One-dimensional analyses that are applied at critical locations within the cross-sections of the embankment and foundation (Tsytovich et al. 1972). In areas where water does not change phase, simple heat-conduction equations are used in the analyses. The Stefan-Boltzmann equation or the Neumann solution to the Fourier equation is used to establish the position of the freezing and thawing front. This one-dimensional method can be used to analyze the transient heat-flow condition.

b. Hydraulic analog computers to analyze two-dimensional simple heat-flow conditions and to establish the location of the freezing or thawing front (Tsytovich et al. 1972).

c. Numerical techniques, such as the finite differences and finite elements methods, to analyze heat flow, including change of phase for two-dimensional problems (Bogoslovskii 1958).

d. Physical models constructed of soil in the laboratory to validate the analytical methods as well as to simulate the prototypes for heat flow.

e. The three-dimensional finite element method of analysis, which accounts for the heat transferred by the seepage water; this is still in the development stage. It is especially useful for analyzing the particular conditions at dam abutments, areas adjacent to water outlet facilities, and short dams (Bogoslovskii 1970).

Of these methods, the one-dimensional analysis is now used most often, although the two-dimensional finite element method, which accounts for the latent heat of fusion, is also frequently used.

Meaningful thermal analysis requires realistic information for defining the thermal properties of soil, the initial temperature distribution within the soil, the geometrical and thermal boundary conditions, and, where appropriate, information about the amount of heat carried by the seepage water. The analysis must also account for the change in the thermal properties of the soil due to a change in phase (i.e. frozen versus unfrozen properties) and to a change in density brought about by consolidation of the soil after thawing. At a given site, the initial soil temperature distribution often is determined by in-situ temperature measurements.

Where accurate meteorological data are available for several years, reasonable estimates of the initial temperature distribution at undisturbed sites have been made using heat balance equations that take into account, directly or indirectly, such thermally significant processes and phenomena as solar radiation, air temperature, wind velocity, evapotranspiration, geothermal gradient, and flowing ground and surface water. The upper boundaries for thermal analyses are usually the interfaces of the atmosphere with the surfaces of the embankment and the natural ground. Some analyses consider the surface of the snow, if it exists, as the upper boundary. In such cases, the depth and thermal properties of the snow are required for the analysis. The lower thermal boundary, which is sufficiently deep in the ground, often is considered to be isothermal, or a constant geothermal gradient is assumed to exist at this boundary. In two-dimensional analyses, the lateral boundary surfaces are usually assumed to be adiabatic.

Although few details are published on the thermal analyses for artificially freezing water-retaining embankments on permafrost, the necessary information is available on methods of analysis developed for freezing shafts, tunnels, and walls to exclude water and soil from excavations during construction in non-permafrost areas (Khakimov 1963, Sanger and Sayles 1978).

The efficiency with which heat passes between the atmosphere and earth materials is computed by using heat-transfer coefficients or factors. The values of the heat coefficients used at the upper boundaries depend upon the color and type of surface exposed to the atmosphere and sun; that is, whether the surface is light or dark and whether it is covered with concrete, gravel, stone, snow, vegetation, or other types of materials.

Methods for calculating heat transfer due to seepage and the convection of water are still quite crude, but numerical methods are being formulated that should eventually improve this computation (Brown and Johnston 1970). The convection of air within a rockfill embankment can transfer large amounts of heat under certain conditions (Mukhetdinov 1969, Mel'nikov and Olovin 1983). Methods for analyzing convection in embankments have been developed and are still under development.

Stability

In evaluating the stability of a water-retaining embankment on permafrost, the functions of each zone within the embankment must be considered. Embankments designed to remain frozen throughout their life consist of an upstream thawed zone and central and downstream frozen zone. The upstream zone not only provides stability against rapid lowering of the reservoir but also serves as a thermal insulator (Bogoslovskii 1958) to protect the central and downstream frozen zone from the heat of the water being retained as well as to protect against mechanical erosion from moving water (i.e. wave action) or the action of ice. The frozen central and downstream zones provide the impervious water barrier and resistance to the horizontal forces exerted on the embankment. The thawing front within the upstream zone and its foundation can be the seat of embankment failure when the shear resistance of the soil decreases due to development of excess pore water pressure. This excess pressure can occur when the thawing front advances faster than the meltwater can escape. The upstream shell of the

embankment is especially susceptible to this type of shear or slide failure when the level of the water being retained by the embankment is lowered rapidly. In determining the stability of the upstream slope, the thawing front is included in the trial failure surfaces.

The stability of unfrozen embankments on permafrost is evaluated similarly to embankments in non-permafrost areas, except that special consideration is given to the low shear resistance that may exist in the foundation at the thawing interface of the permafrost. A portion or all of this interface is included as part of the trial failure surfaces that are investigated in the stability analvses. The shearing resistance at this interface is a major consideration in assessing the resistance to horizontal forces. To increase the shearing resistance at the thawing front, vertical sand drains terminating in an intercepting horizontal drainage system have been used successfully (Johnston 1969, Gupta et al. 1973) to accelerate the dissipation of excess pore water pressure.

<u>Maintaining the frozen state of water-retaining embankments</u>

Techniques for maintaining embankments in a frozen state include both natural and artificial cooling. Natural cooling is usually applicable for small embankments with heights of 10 m or less where the natural cold atmosphere freezes the top and the exposed slopes of the embankment. Techniques that have been used or proposed to encourage natural freezing include: removal of snow from the downstream face, by equipment or by constructing horizontal wind "vanes" that direct the wind parallel to the surface of the dam and blowing snow away from the downstream slope, placing a shelter over the downstream slope to keep snow and rain off the surface and to shade it from the sun; collecting a thick snow cover on the downstream surface during the early spring and providing for winter ventilation at the embankment surface by constructing duct work beneath the snow and ice on this surface; protecting the downstream toe from the warming effect of the tailwater by using berms; and keeping the foundation frozen during construction (Borisov and Shamshura 1959, Tsvid 1961). Tsytovich (1973) has pointed out that the natural cooling of soils on the downstream slope of an embankment dam will result in freezing to a maximum depth of about 10 m in a severely cold climate if the surface is kept clear of snow. Therefore, auxiliary cooling is required if freezing is to be accomplished at greater depths.

Frozen earth dams with heights of up to about 25 m have been built in the USSR using artificial refrigeration. The refrigeration systems include: the circulation of naturally chilled air, the circulation of artificially chilled liquid brine, and the installation of a series of automatic thermal devices such as thermal piles. The cooling elements in each of these systems consist essentially of vertical pipes installed along the axis of the embankment. Each pipe extends down through the embankment into the permafrost foundation. When air is used as a coolant, each vertical pipe has a smaller pipe located concentrically inside it. Air is circulated down the annulus between the two pipes to a point near the bottom of the outer pipe where the air enters the inner pipe, and is returned up to the atmosphere through an exit manifold (Biyanov and Makarov 1978). The air is allowed to flow through the system only when its temperature is lower than some predetermined temperature, say about -15°C. Cooling by air can be used effectively at locations where the mean annual air temperature does not exceed -5°C (Trupak 1970). In regions of high humidity, rust and ice can form inside the freezing pipe, resulting in reduced heat removal efficiency and even plugging the pipes completely (Sereda 1959, Gluskin and Ziskovich 1973, Biyanov and Makarov 1978). When liquid brine systems are used, they consist of a refrigeration unit with a heat exchanger for cooling a heat transfer liquid or brine, which is circulated through the cooling elements in the embankment. Calcium chloride solution has been used as a brine, and in one instance the system had to be converted to an air-cooling system when the calcium chloride leaked into the frozen soil and melted it (Borisov and Shamshura 1959, Tsvetkova 1960). The cooling brine must not contain impurities or water that will deposit or freeze in the pipes and restrict the flow of brine or plug the pipes, so corrosion inhibitors are incorporated into the brine In addition, the piping systems are made of materials that resist the attack of the circulating brine (Borisov and Shamshura 1959). Thermal devices (e.g. thermal piles) that have been used in the USSR to freeze an impervious zone in a dam usually are of the single-phase gravity type that use kerosene as a transfer liquid (Gapeev 1967, Biyanov and Makarov 1978), although the two-phase thermal device that uses ammonia as a transfer fluid is now used in the USSR. In North America, two-phase thermal piles are used to a limited extent to maintain river

levees in the frozen state. Both the single-phase and the two-phase systems can perform satisfactorily.

Embankment dams on permafrost in the USSR that are higher than 25 m are usually designed as unfrozen rockfill dams on a thaw-stable bedrock foundation. The temperature of the foundation is monitored to follow the movement of the thawing front in the foundation, and in at least one instance cement grout was periodically injected into the thawed zone of the foundation as the thawing front advanced in depth (Demidov 1973). It has been observed that air circulating within the downstream rockfill section of an embankment dam by natural convection has resulted in ice accumulation from moisture condensing on the cold rock surfaces near the downstream surface of the dam in its upper reaches, and that the foundation freezes rather than thaws near the downstream toe of the dam (Kamenskii 1973). Preliminary studies (Mel'nikov and Olovin 1983) indicate that cold winter air sinks through the downstream rockfill zone to the base of this zone, where it encounters the relatively warm, moist foundation. The air is warmed and picks up moisture at this point, then rises through the rockfill where the moisture is deposited on the colder rock surfaces located near the surface of the downstream slope. In one case, the heat removed from the foundation by this convection has frozen at least part of the talik (Mel'nikov and Olovin 1983) that existed beneath the river bed before the dam was constructed.

Experience in operation and construction

Experience in the USSR and North America has demonstrated that water-retaining embankments can be constructed and successfully operated on permafrost if appropriate precautions are taken. In the USSR, at least five intermediate-size embankment dams with heights ranging from 20 to 125 m (Biyanov 1973, Tsytovich et al. 1978, Johnson and Sayles 1980, Johnston and MacPherson 1981) are now in operation on permafrost. Several smaller embankments have been functioning for many years. The oldest known embankment dam on permafrost was built in 1792 at Petrovsk-Zabaykalskiy and continued in operation until 1929 without incident (Tsvetkova 1960, Tsytovich 1973). Many of the smaller dams performed satisfactorily; however, some have had problems, especially in controlling the seepage around the water outlet facilities (see Table 1). (The map in Fig. 1 shows some of the major rivers and cities near the dams described in this report.)

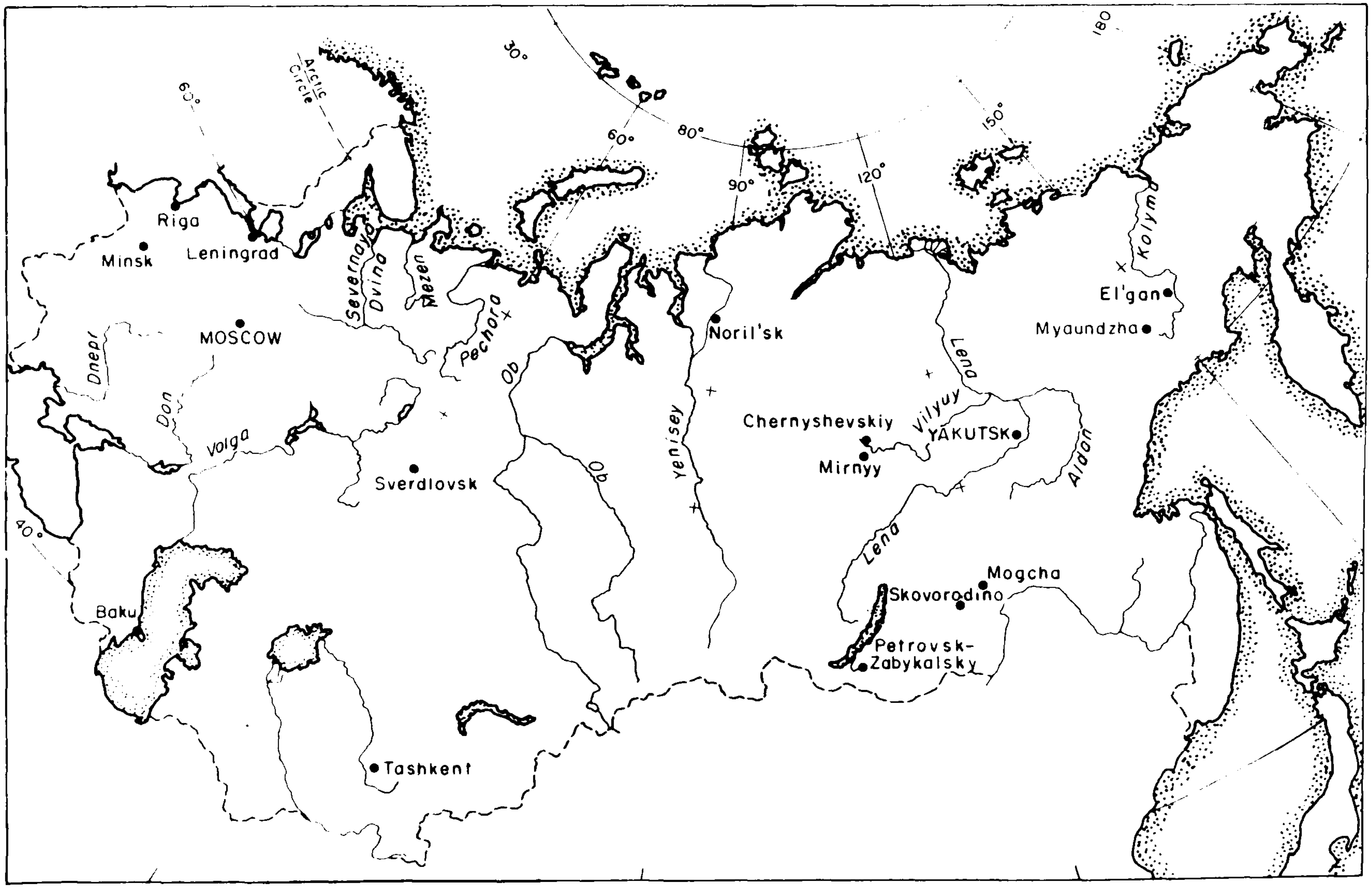

Figure 1. Major rivers in the USSR.

Much experimentation to develop techniques for creating and maintaining frozen embankments on permafrost has been conducted in the USSR. One pioneer project was a 10-m-high frozen dam built in 1942 on the Dolgaia River at Noril'sk that was initially cooled by circulating a calcium chloride brine through vertical freezing pipes installed along the centerline of the dam. These pipes extended through the talik beneath the river bed. Brine leaks made it necessary to change the circulating fluid from brine to air. The dam performed satisfactorily; however, only after an ice sheet was created on the downstream slope to stabilize the thermal regime (Borisov and Shamshura 1959, Tsvetkova 1960).

Two water supply dams located in the Irelyakh River near Mirnyy, Yakutia, USSR, were built on permafrost using innovative methods for that area. The older one, a temporary dam built in 1957, is a 9-m-high earthfill dam with a timber crib filled with loam serving as an impervious core (Lyskanov 1964). This core extends down to the fissured sedimentary bedrock. The spillway consists of a timber flume with wooden crib wing walls. Temperature observations over a 7-yr period of operation showed that the foundation thawed to a depth of approximately 50 m due to the flow of water through the spillway (Johnson and Sayles 1980). The average temperature of the permafrost in this area was about -2°C. The second dam, completed in 1964, is a 20.7-m-high earthfill embankment located about 2 km upstream from the temporary dam (Biyanov 1966, Semenov 1967, Smirnov and Vasiliev 1973). This main Irelyakh River dam is founded on about 8 m of Quaternary deposits consisting of frozen sandy gravel and silty clays having up to 60% ice content. Beneath this deposit lies fractured dolomitized limestone and marl with ice content up to 10%. The embankment cross section consists of a large, silty clay central section with zones of sand beneath layers of gravel on both the upstream and downstream slopes. A silty clay cutoff extends through the Quaternary deposits to bedrock along the centerline of the dam.

Because thawing of the ice-rich foundation soils would cause unacceptable settlements, a line of vertical cooling pipes was installed at 1.5-m spacing along the axis of the embankment to establish a positive seepage cutoff (Fig. 2). The cooling pipes (Fig. 3) were designed to extend down through the embankment and about 3 m into the foundation, however, during construction the permafrost thawed an additional 6 m and the cooling pipes were consequently extended to this depth.

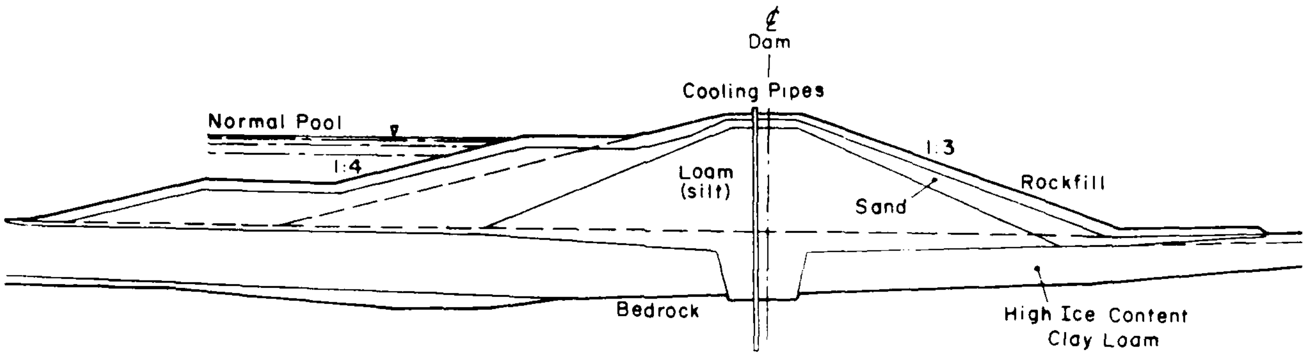

Figure 2. Cross section of the second Irelyaka River Dam near Mirnyy, USSR (after Biyanov 1966).

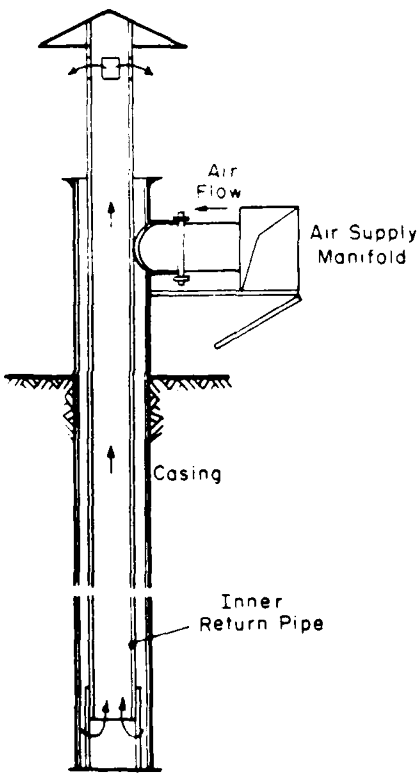

Figure 3. Cooling pipe (after Biyanov 1966).

After operating the cooling system the first winter, the dam foundation and core became almost entirely frozen along a line of merged ice-soil cylinders that froze around each freezing pipe. Only two unfrozen sections were detected and these became frozen during the second winter (Johnson and Sayles 1980).

To reduce the velocity of seepage from the reservoir in the talik beneath the embankment during the initial operation of the cooling system, an additional row of cooling pipes was installed along the downstream toe of

the dam across the old river bed. After the central ice-soil cylinders had merged, chilling at the downstream toe was no longer required. Horizontal cooling pipes were installed beneath the concrete spillway located on the left abutment. To protect the adjacent embankment from thawing as a result of heat from the water discharged over the spillway, a line of vertical cooling pipes was installed along the embankment side of the spillway discharge chute, which is paved with concrete slabs on a gravel filter. After about 10 years of operation with a permanent reservoir, temperature measurements in the spillway area showed that the permafrost was thawing beneath the spillway chute toward the embankment. As a result, not only was the thawing front advancing toward the dams but the concrete slabs also became misaligned and moved from their original positions, thus inducing further degradation of the permafrost. To arrest this thawing, additional freezing pipes were installed and the spillway crest was raised to increase the storage capacity and thereby reduce the amount of water discharged during periods of high runoff (Anisimov and Sorokin 1975).

The Irelyakh River dam has had a permanent pool behind it for over 18 years, and although degradation of the permafrost in the spillway area had to be arrested, the embankment has performed satisfactorily as a result of proper maintenance.

It is interesting to note that no especially high embankment dams (i.e., higher than about 50 m) have been built on permafrost with frozen soils as the water seepage barrier. The larger embankments, all located in the USSR, are founded on incompressible bedrock (Tsytovich 1973) and are designed as thawed embankments. One such embankment that has impounded a reservoir since 1969 is the dam for the Vilyuy Hydroelectric Station located on the Vilyuy River at the town of Chernyshevskiy in Yakutia (see Fig. 1 for approximate locations). The site of the dam and reservoir is underlain by Palaeozoic and Mesozoic sedimentary and volcanic rocks. Intrusive rocks are from the lower Triassic period. At the dam site, the rock to a depth of 30 m contains small fissures, some of which were open, containing only ice.

The average air temperature at the site is -8.2°C and permafrost temperatures vary from -2 to -6°C depending upon the orientation of the ground slope with respect to solar radiation. Permafrost thickness varies from 200 to 300 m, but a talik extends entirely through the permafrost beneath

the river bed at the dam site. The cross section consists of a rockfill shell with an inclined clay zone protected by two-layer filters upstream and downstream (Fig. 4). A concrete pad enclosing a grouting gallery forms the base of the impervious zone. Initial grouting into 4-m-deep holes was performed to reinforce the blast-shattered rock and to reduce seepage beneath the concrete pad. Further grouting of the bedrock fissures is accomplished as the ice melts from these fissures. The requirement for further grouting is indicated by temperature sensors and pioezometric measurements (Demidov 1973).

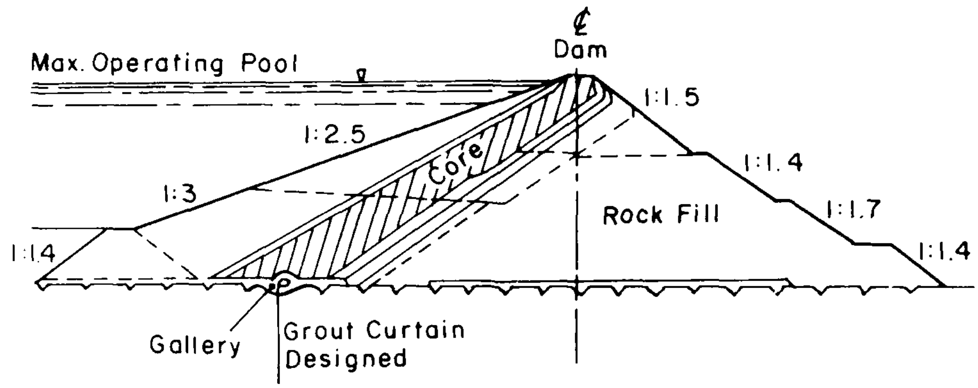

Figure 4. Cross section of Vilyuy Dam.

During the construction and operation of this dam, ice built up in the pores of the downstream rockfill (Mel'nikov and Olovin 1983). Studies of the circulation of air within the rockfill indicated that the talik beneath the former river bed was freezing. Moisture is entering the rockfill pores from convection, from precipitation, and from occasional tailwater backup. The ice formed from the tailwater is solid and remains at the base of the fill, while that from precipitation is distributed in the rockfill depending upon its temperature distribution. As the voids in the backfill become filled with ice, air currents are damped and the freezing of the talik ceases (Mel'nikov and Olovin 1983). The embankment dam has been operating successfully since its construction in 1969.

Other high-water-retaining embankments constructed on bedrock permafrost in the USSR are those at Ust-Khantaysk and the Kolyma Hydroelectric Power Station (Evdokimov et al. 1973, Gluskin et al. 1974, Tsytovich et al. 1978). Although there is some information describing the construction of the Ust-Khantaysk Dam (Gluskin and Ziskovich 1973, Tsytovich et al.

1978, Gluskin et al. 1974), construction details of Kolyma Dam have not been published, and its completion has not been announced as yet. Details of the performance of these dams are not available in western literature at this time. It is assumed that they are performing as designed.

Two specific problems that have been given special attention in the USSR literature are frost heaving and thermal cracking of embankments. Since frost action can occur to depths of a few meters at the crest of an embankment, non-frost-susceptible soils, anti-heaving salting, and heating have been suggested as measures to counteract this problem (Kronik 1973, Tsytovich et al. 1978). Transverse thermal cracking of embankments has been observed during and after the winter season. Cracks in one of the irrigation dams on the Suola River near Yakutsk were investigated by Grechishchev and Sheshin (1973). They found that the cracks occur within 1.5 m of the vertical walls of the wooden outlet structure. To protect against this type of cracking, a layer of gravel 2-m thick is being used at the crest of embankments on permafrost in the USSR. Grechishchev suggested embedding horizontal wooden rods near the crest parallel to the axis of the embankment to act as reinforcement in the soil and prevent these cracks. A method of calculating the longitudinal thermal deformation of embankments has been developed (Greschishchev and Sheshin 1973) and the calculated crack widths are in good agreement with those observed in the embankment under investigation.

In Canada, the literature does not record the construction of an embankment designed as a frozen structure on permafrost but it does reveal that several small dikes (Johnston and MacPherson 1981) and a waste impoundment (Thornton 1974) were designed and constructed as the thawed type of embankment on permafrost. In these designs, the amount of thaw consolidation that would occur in the foundation was estimated, and the embankment height was increased to accommodate the anticipated settlement. As an alternative to overbuilding the dikes, the design heights can be maintained by periodically adding embankment material to the crest of the dikes as settlement progresses. In some instances, vertical sand drains (Johnston 1969, MacPherson et al. 1970) can be installed in the permafrost foundation beneath the embankment to reduce pore pressures and hence increase the shearing resistance of the soil while thawing occurs (Fig. 5). The differential settlements associated with this type of design can lead to trans-

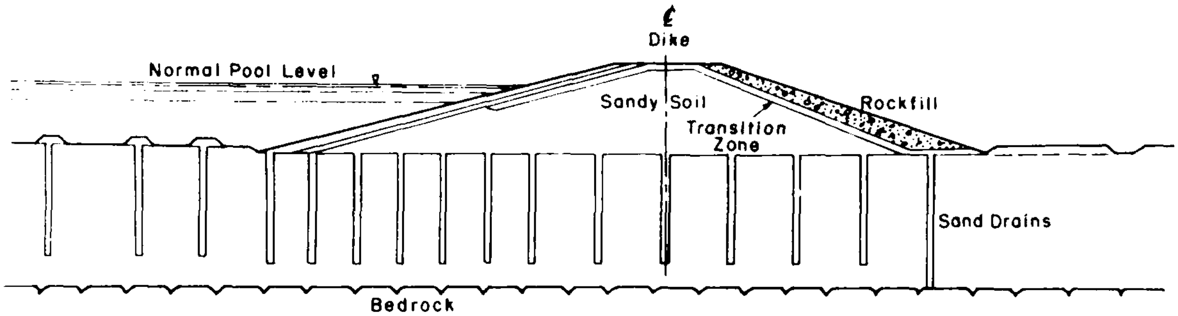

Figure 5. Dike of the Kelsey Reservoir, Canada.

verse cracking of the embankments. To accommodate the cracking, the embankments constructed in Canada were constructed of soils that are self-healing in nature (Johnston and MacPherson 1981). Essential to this type of design is a continuous observation program throughout the life of the structure.

Other examples of thawed embankments founded on permafrost in northern Manitoba, Canada, are the dikes in northern Manitoba at Kelsey (MacDonald 1963), Kettle (MacPherson et al. 1970) and Long Spruce (Keil et al. 1973) hydroelectric generating stations (see Fig. 6 for approximate locations). To date, these embankments appear to have been performing as envisioned by their designers.

In the United States, one 24-m-high water-retaining embankment, five small embankment dams less than 6 m-high, and a few levees have been constructed on permafrost in Alaska and one in Thule, Greenland. The small water-supply dams at remote villages are of the frozen type of design and are without artificial cooling. Although some have been in operation for more than 30 years (Davis 1966, Fulwider 1973), no serious problems have been reported. The largest embankment dam founded on permafrost in Alaska (Fig. 7) is located near Livengood on Hess Creek (Rice and Simoni 1963, Kitze and Simoni 1972). This combination hydraulic fill and rolled-earth-fill structure was completed in 1946 to a maximum height of 24 m. The foundation consists of silt and ice to a depth of approximately 6 m overlying a 6.5-m-thick deposit of a variable mixture of frozen clay, silt, sand, gravel, and fragments of chert rock. Beneath this deposit and overlying the fractured chert bedrock is a 6.5-m layer of frozen coarse sands and gravels containing considerable ice. After stripping the site, the hy-

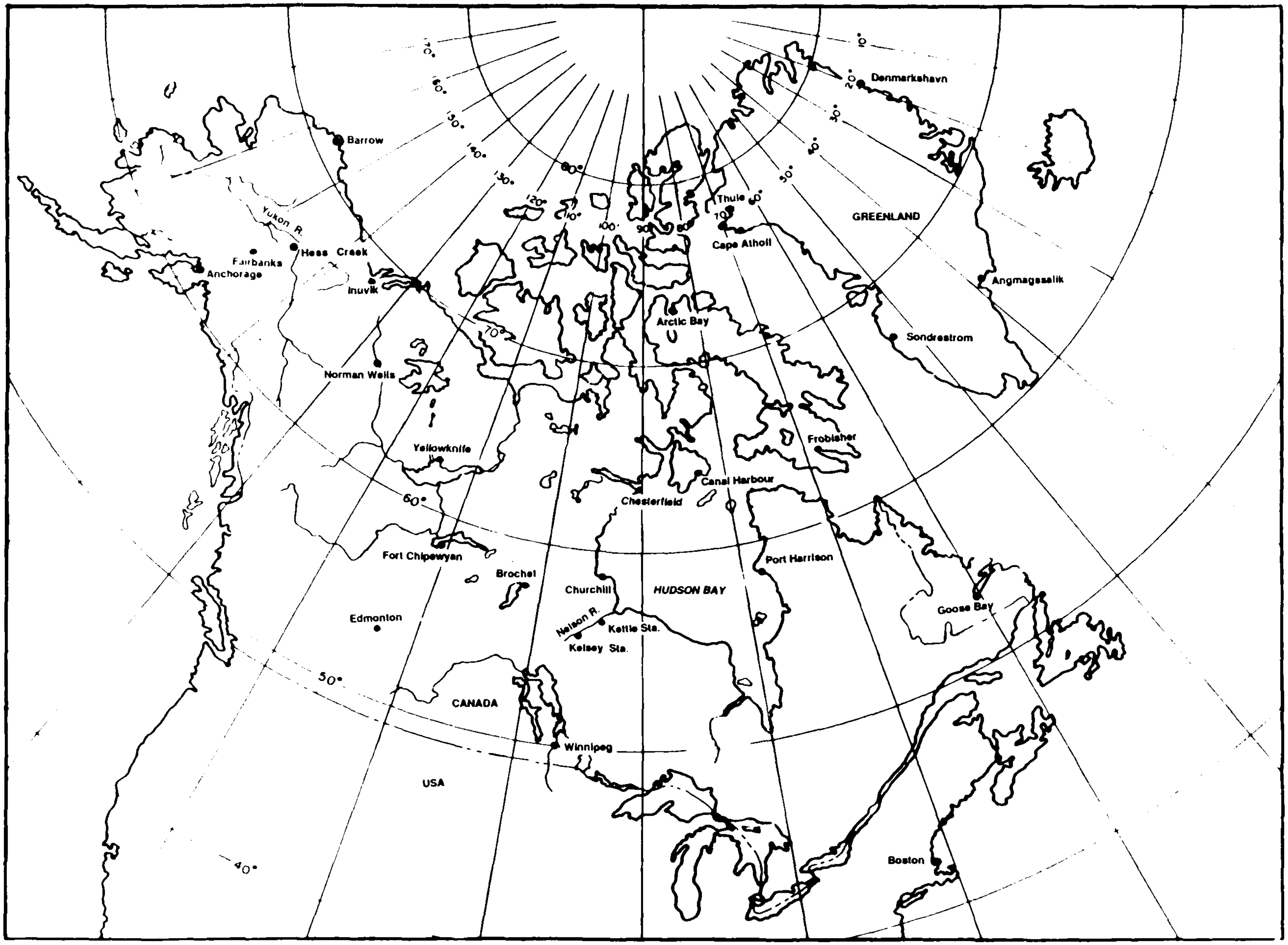

Figure 6. Canada and Alaska location map.

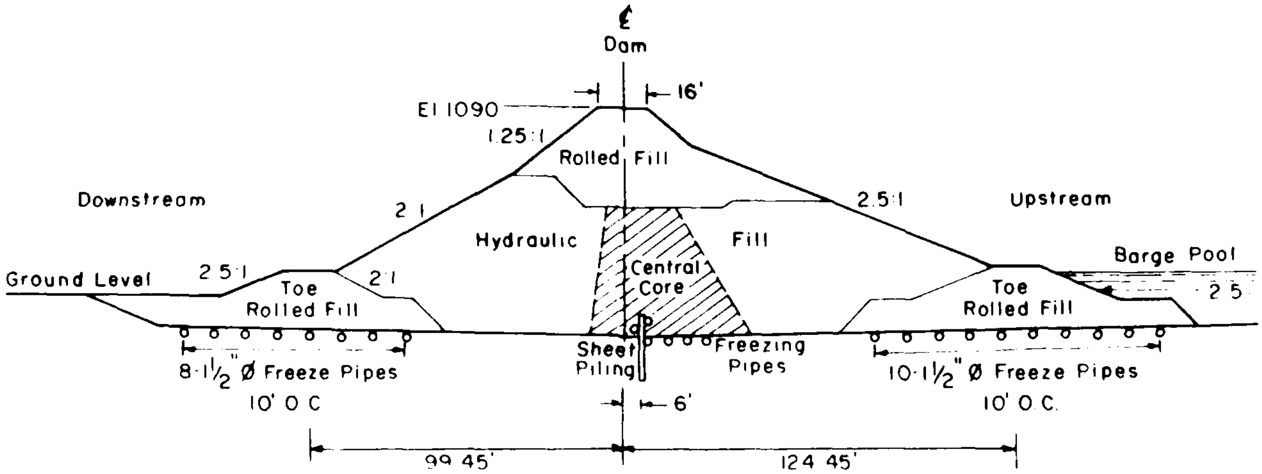

Figure 7. Typical embankment section, Hess Creek Dam, Alaska (after Kitze and Simoni 1972).

draulic fill was placed directly on the frozen silt. Horizontal cooling pipes were installed at the surface of the foundation to provide artificial refrigeration to keep the foundation frozen during construction. Steel sheet piling embedded in permafrost and projected 2 to 3 m up into the hydraulic fill was used to improve the seepage cutoff. Since this dam only retained water during the short summer mining period each year, the reservoir was lowered every autumn to take advantage of winter cooling to preserve the permafrost foundation and refreeze the embankment. This dam performed satisfactorily from 1946 until 1958, when the mining operations were stopped for economic reasons. The major operating deficiency in the system was a water outlet tunnel located remotely from the dam. It completely collapsed some time after the mining operation ceased. Then in 1962, the overflow from the spring runoff washed out the timber spillway that was located on the right abutment of the dam. Because the spillway failed by washing during spring runoff, the dam was breached and is useless even though the embankment itself remains intact today.

Embankment dams on permafrost: recorded failures and problems

Embankment dams on permafrost have been built and successfully operated in Canada, the USSR, and Alaska. A number of failures have been report-

ed in the USSR and one in Alaska. Table 1 lists 15 embankment dams that encountered difficulties; some of the problems were corrected, but several ended in disaster. An examination of the table reveals that most of the difficulties arose because insufficient attention was given to establishing and maintaining a reliable frozen condition and to controlling seepage. It should be noted that often the thawing and seepage in a frozen embankment or foundation are initiated adjacent to the spillway or outlet works. This, of course, indicates that inadequate cooling or cutoffs were established at these points. Other problems described in the table can be traced to the construction procedures and the control of earth placement. In some cases, adequate thermal protection was not provided for the foundation and adjacent areas during construction. In other cases, the soil placed in the frozen state was insufficiently compacted.

Table 1 includes only a portion of the problems that have been referenced in the literature. Although several papers on embankment dams on permafrost have been collected and translated, it is reasonable to assume that there are many more failures, either unreported or not available in this limited bibliography. However, the dams that are listed indicate the problems that must be addressed if safe and economical embankment dams are to be built on permafrost.

RESEARCH REQUIRED

The design, construction, and maintenance of safe water-retaining embankments in the Arctic and Subarctic is strongly dependent upon such considerations as structural stability, seepage control, the handling of materials, erosional control, and the environmental effect of the impoundment. The following is a list of areas that need further research:

a. The development of analytical methods for determining and predicting the thermal regime within and beneath water-retaining embankments on permafrost when ground water seepage occurs and where three-dimensional heat flow is important.

b. The development of effective methods for controlling the thermal regime and seepage, especially at locations contiguous to spillways and outlet works for embankments on permafrost.

c. The development of drainage systems that will not become plugged with ice.

d. The analysis of existing techniques and the development of new ones for constructing frozen and unfrozen embankment dams on permafrost during both the summer and winter construction seasons while maintaining a frozen foundation.

e. The development of more accurate analytical procedures for determining the stability of embankment and natural and cut slopes in permafrost during thawing.

f. The development of accurate methods that use electromagnetic, geophysical, and other types of tools for determining the extent and depth of permafrost, massive ice inclusions, and types of soils at proposed embankment sites.

g. The development of instrumentation for monitoring the construction and performance of embankments on permafrost, with special attention to early detection of seepage that occurs in a "frozen" embankment or its foundation.

h. The determination of the effects of impoundments on water chemistry in reservoirs and streams over permafrost.

i. The development of biological procedures for restoring landscapes that have been disrupted by the construction of reservoirs in arctic and subarctic areas.

j. The determination of the tolerance of cold-dominated vegetation to periodic inundation.

k. The validation of existing methods for predicting the hydrological characteristics of catchment basins on permafrost.

l. The development of effective methods for controlling water and ice erosion of embankments, cuts, and natural slopes of reservoir walls in permafrost areas.

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SECTION IV

AN ANNOTATED BIBLIOGRAPHY

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This Soviet paper describes the repair work on a 21.4-m-high frozen earth city water supply dam that was breached because a reservoir was impounded behind it before all the cooling pipes were installed to freeze the central portions of the dam. The dam consisted of a homogeneous cross section of loam (silt) founded on a 230 m thick layer of permafrost. The dam was located where the mean annual air temperature is -10.6°C and the permafrost temperature is -7°C.

Comment: It is interesting to note that without artificial refrigeration this dam could not remain frozen despite the cold climate and low permafrost temperature.

Are, F.E. (1973) The reworking of shorelines in the permafrost zone. In Permafrost: USSR Contribution to the Second International Conference Proceedings, Yakutsk, p. 59-62. Washington, D.C.: National Academy of Sciences, 1978.

This article summarizes and describes the processes that are at work in the retreating shorelines of water bodies located on permafrost, and gives methods for predicting the role of retreat as well as the final limit of the shoreline retreat. Three fundamental and independent processes at work in shoreline reworking are:

(1) Thermal abrasion: The disintegration of the shore zone under the influence of the mechanical and thermal energy of moving water.

(2) Thermal denudation: The disintegration of the shoreline under the influence of the thermal energy of the air and solar radiation.

(3) Thermokarst: The thawing of the bottom of the water under the influence of the thermal energy of the water, leading to subsidence of the bottom surface.

The character of the reworking of the shoreline depends greatly upon the ice content of the soils. The critical ice content is that amount which, when melted from the soil, will lower the surface of the shore below the water level to a depth where the mean annual temperature of the water is above freezing. If the amount of subsidence caused by the ice thawing leaves the shore above this level then the retreat of the shoreline depends only on abrasion. If the shore is left below this level, thawing of the permafrost will occur at the bottom of the water body, which in turn will cause further exposure of the shore slope and hence slope instability with-

out abrasion. Retreat rates of shorelines are indicated by the slope of the offshore profile. Four main slopes are: inclined, inclined with perpendicular lower part, perpendicular, and stepped. A perpendicular shore with wave-cut notches indicates rapid retreat of the shoreline. If the shore is inclined, or inclined with a lower perpendicular part, then the shoreline is retreating at a rate approximately equal to the rate of thermal denudation. An approximate quantitative method for estimating the rate of retreat of the shoreline is to determine the depth of the talik beneath the water body at a known distance from the shoreline. Then by the Stefan equation, or some other method, compute the time required for the talik to reach this measured depth.

By dividing this time into the measured distance from the shoreline, the rate of shoreline retreat can be estimated. In making this estimate, the amount of thaw consolidation must be taken into account to arrive at the proper depth of the talik. The final limit of shoreline retreat can be estimated by computing the elevation of the adjacent terrace after thaw consolidation of the terrace soils has been completed and comparing this elevation with that of the water depth where the mean annual temperature is above freezing. The lateral location where these two points coincide is an estimate of the final shoreline retreat.

Comment: This paper is pertinent to the shore changes of a reservoir on permafrost, especially at the abutments of a dam on permafrost.

Belikov, M.P., G.A. Panasenko, and A.S. Antsiferov (1968) Earth dam in permafrost region constructed with plastic waterproof barrier (in Russian). Translated from Gidrotekhnicheskoe Stroitel'stvo. Hydrotechnical Construction, Oct., no. 10, p. 878-880.

This paper describes the installation of a polyethylene membrane to serve as a water barrier for portions of a 10-m-high experimental dam on continuous permafrost. The membrane was placed on the specially prepared surface of the upstream slope of the dam, then covered with mine waste material having a thickness of 1 m at the toe and decreasing to 30-40 cm at the top. The top and bottom of the membrane were anchored in trenches.

Comment: The installation described in this paper was for experimental purposes, and observations of its performance were made for only about one year. Apparently the membrane performed satisfactorily for that period.

Biyanov, G.F. (1973) Experience in building dams on permafrost in Yakutia (in Russian). In Permafrost: USSR Contribution to the Second International Conference, Yakutsk, p. 125-132. National Research Council of Canada, 1978. Washington, D.C.: National Academy of Sciences. USA Cold Regions Research and Engineering Laboratory, Translation 438.

The construction rockfill dam on the Vilyuy River and the earth dam on the Irelyakh River are described. The impervious zone of the Vilyuy Dam was placed at temperatures down to -20°C in the unfrozen condition by: ex-

cavating, transporting and stockpiling in the summer, mixing calcium and sodium chloride salts in the stockpiled loam (20% by vol.) volume; heating the borrow area electrically (40 kW-hr/m^3), heating the dump truck beds using engine exhaust gases piped through the double sheathing of the truck beds; covering the loaded truck beds with blankets; covering the soil layer with a polymer film immediately after unloading; thawing the frozen crust of previously placed fill with heat from junked aircraft jet engines (temperatures 300 to 500°C), then treating the fill surface with a salt solution; removing large frozen clods from the fill. Efforts to place fill at -50°C were not successful because of frequent breakdown of equipment. The present lower temperature limit is -40°C and is established because the construction equipment has limited capability at lower temperature. Where unfrozen soil was placed on frozen embankment, stratification occurred and soil in these areas had to be replaced. The thickness of rock fill layers during placement varied depending upon the construction schedule of the impervious zone and filter, but thicknesses of 10, 15 and 25 cm were used. The rockfill was compacted with vehicle traffic only. The dam on the Iyerelyy River near the town of Mirnyy and one on the Oyaar-Yareg River were described as dams requiring artificial refrigeration for seepage control. Temperature profiles and sections for the dams on the Vilyuy and Iyerelyy Rivers are shown in Figures.

Comment: This paper is a brief summary of information that has been published in other papers in greater detail. See Biyanov (1966).

Biyanov, G.F. (1970) Construction of dams in the Canadian North (in Russian). Translated in Hydrotechnical Construction, Jan., no. 1, p. 75-83.

This article describes the embankment dams near Whitehorse, the Kelsey dikes, and the proposed Kettle hydraulic complex. The earth fill dam near Whitehorse consists of a clay core with a gravel shell founded on bedrock. Although permafrost does not present a problem at this site, cracks developed at the crest of the core due to freezing. These cracks were repaired by injecting lignocite into the area. The Kelsey dikes were constructed higher than necessry for water impoundment to allow for settlement when the ice-rich permafrost thawed. Also sand drains were installled beneath the embankment to increase the consolidation rate as the foundation thawed. It was estimated that 1.5-m settlement would occur. After seven years of operation 90 cm of settlement occurred in the foundation and 60 cm in the dam. At the Kettle Hydroelectric Plant the central core of the main dam is founded on bedrock and the toes are to be supported on ice-rich permafrost covered with a drainage blanket. At the right abutment, the core is to be founded on compact, cemented sandy gravelly soils with drainage curtains extending down to bedrock. One of the saddle dikes is to be constructed on frozen sandy clay that is to be allowed to thaw during the operation of the reservoir.

Comment: This summary article was written before the Kettle Hydroelectic Plant was completed. The paper indicates that the Soviets consider the thaw-consolidation type of design used at the Kelsey dikes to be un-

usual. More detailed information on the dams described can be obtained in Canadian articles on these dams. See Johnston (1965, 1969) and MacPherson et al. (1970).

Biyanov, G.F. (1966) Experience in building a hydroelectric generating station under permafrost conditions. Translated from Gidrotekhnicheskoe Stroitel'stvo. Hydrotechnical Construction, no. 10, p. 1-5. National Research Council of Canada, Technical Translation No. 1353, 1969.

The construction of the 20-m-high water supply dome for the city of Mirnyy located on the Irelyakh River (a tributary to the Vilyuy River) is described in detail. This dam is one of the largest dams with a frozen core on permafrost and the first in the Soviet far north. The mean annual air temperature at this site is -8.2°C and soil temperature is about -3.0° at 10 m depth. The dam was built as a thawed dam with a seepage cutoff trench extending to bedrock through high ice content (60% up to 90%) silt in the left abutment area. Portions of the bedrock are weathered limestone and dolomite. Some of the rock was weathered to depths of 40 m with fractures filled with ice. Other portions of the bedrock were weathered to a silty clay which has high bearing strength and is practically impervious when frozen. A frozen core was formed along the axis of the embankment by installing vertical cooling pipe assemblies through which cold air (-15°C or colder) was blown in the winter months. These cooling pipe assemblies consisted of two concentric pipes (inner pipe 139 mm in diam., and outer pipe 219 mm in diam.) and extended 3 m into the foundation of the dam. Cold air was forced down through the annulus between the inside and outside pipes, then discharged up through the inside pipe. A sliding valve was installed at the inlet of each pipe to balance the air flow in the system. The construction scheduled called for the foundation to be prepared in the winter and a 1.5-m-thick layer of clay was placed on the prepared areas to prevent thawing during the summer. The talik was allowed to freeze before excavation to provide a working surface for equipment. The drilling and blasting method was used to loosen the frozen soils. The embankment was constructed of thawed soil. Some of the thawed sand and loam (silt) materials were stockpiled in 12-m-high piles during the summer. The top 3 m of frozen soil was removed the following year to start placement of the unfrozen embankment. Experiments with placement of soil at optimum moisture content were conducted at the site. These experiments included:

(a) Drying the soil by placing it on pipes through which 300°C gas was forced by an airplane turbojet. This system was quite uneconomical because the soil adjacent to the pipe dried completely and formed an insulative cover around the pipe while soil away from the pipes remained frozen.

(b) Heating the soil surface under tarpaulins.

(c) Compacting the frozen soils in 0.4- to 0.5-m-thick layers, then placing electrodes in the silt, which was saturated with a calcium chloride solution to improve electrical conductivity. High ice content soils placed

in this manner could not be compacted to the required density because of the high water content that resulted from melting the ice. Seepage created serious difficulties during the period when a continuous frozen cutoff was being formed because the "warm" moving water in the talik could not be frozen by the main cooling pipe system. To cut off the seepage it was necessary to install a cooling system at the downstream toe of the dam across the talik. Ater the latter cooling system reduced the velocity of the seepage water the main cooling system was able to complete the frozen cutoff across the entire dam. Horizontal cooling pipes were used to freeze a cutoff beneath the spillway.

Comment: This paper gives an excellent description of the construction of the water supply dam at Mirnyy. Biyanov was in charge of construction at the site.

Biyanov, G.F. (1966) Discharge and blocking up the river during construction of the Vilyuy Hydroelectric Power Station (in Russian). Translated from Gidrotekhnicheskoe Stroitel'stvo. Hydrotechnical Construction, no. 2, p. 1-5. National Research Council of Canada, Technical Translation 1353, 1969.

This paper describes the construction procedures and the quantities and velocities of discharge when the river was diverted from its bed to the construction trench. The river was blocked by end-dumping large rock from one shore and progressively closing the river channel within a period of three hours and 45 minutes. The closure was made on 31 October 1964 when the discharge was about 77 m^3/sec. The closure at this time of year required that the clay material in the inclined core be placed under severe winter conditions.

Bogoslovskii, P.A. (1970) Analytical calculation of a three-dimensional stationary, steady-state temperature condition of a dam (in Russian). Sbornik trudov po gidrotekhnike i gidrostroitel'stva pri stroitel'stve plotin v suravykh klimaticheskikh usloviyakh. USA Cold Regions Research and Engineering Laboratory, Translation 601.

This paper presents solutions to the Laplace equation for two cases with idealized boundary conditions at the abutments of homogeneous dams without seepage. The first case considers that the reservoir is in contact with the horizontal surface of the ground and occupies one quadrant of a rectangular coordinate system. This case does not take into account the relief of the valley, dam or river so it can be applied only to flat relief, i.e, very gentle slopes of the dam and the valley. The second case considers a narrow reservoir bounded by two banks and the dam and with flat relief. A graphic comparison between the three-dimensional and two-dimensional analyses shows a considerable difference for the narrow reservoir. Through consideration of the different conductivities of the thawed and frozen soil, the isotherms within the dam and beneath the reservoir were computed. The computation indicates that the abutments can provide considerable cooling to the dam, especially in narrow valleys.

Comment: The analysis presented is for highly idealized conditions, i.e. flat surfaces exposed to air and water, uniform temperatures at surfaces, straight lines and right angle boundaries. However, the method would be useful at least as a preliminary estimate of the thermal regions.

Bogoslovskii, P.A. (1958) Investigations on the temperature regime of earth dams under permafrost conditions (in Russian). Nauchnye Doklady Vysshei Shkoly, Stroitel'stvo, no. 1, p. 228-238. USA Cold Regions Research and Engineering Laboratory, Translation 22.

This article presents results from two-dimensional analyses of the temperature regime of earth dams on permafrost for transient and steady-state conditions including seepage and non-seepage cases. For the transient case with no seepage, heat transfer is assumed to be by conductivity and therefore the Fourier differential equation is applied by means of the finite difference method. The zero isotherm is located by using the Stefan condition in the finite difference method also. Similarly the steady-state case was analyzed using the finite difference method but applying the Laplace equation.

A 25-m-high homogeneous embankment dam was analyzed for the following conditions:

a) No seepage for the transient temperature regime

b) Initial condition - unfrozen embankment on permafrost

c) Boundary conditions - constant annual average temperatures

d) Soil thermal properties - constant

e) Results: In 20-30 years a thawed layer of soil was enclosed in the frozen embankment a short distance above the foundation. Further freezing would produce expansion due to the change in phase of water in the unfrozen layer and hence possible damage would occur to the embankment.

A physical model was constructed in the laboratory where boundary temperature conditions were applied to simulate field conditions and temperatures were measured to validate the method of mathematical analysis. In analyzing the model, the thermal resistance at the air interface was considered by using a fictitious material having the same thermal conductivity as that of the soil but with no heat capacity.

In analyzing a dam embankment for the steady-state thermal regime, account is taken of the change in the thermal properties of the soil with temperature change; the geothermal heat by superimposing isotherms from a simple geothermal analysis onto those of the steady-state analysis; and the seasonal temperature variation by analyzing the soil layers lying along the streamlines as one dimensional insulated rods. It was concluded that: the limiting temperature regime within the embankment was reached within a few decades, i.e. with the expected life of the structure; centuries are re-

quired to achieve a steady-state condition in the permafrost foundation; the downstream portion of the dam serves as an anti-seepage barrier and a support against horizontal forces, the upstream portion, which is thawed, serves as thermal insulation for the downstream frozen zone to protect it from the reservoir water heat; the active zone should not extend from the crest to the reservoir level to avoid seepage problems; and the fill in the active zone should be nonfrost-susceptible.

A thermal analysis of a pervious embankment with a downstream drain on an impervious permafrost foundation showed that with a constant seepage the temperature in the embankment stabilized in about a half year.

The general conclusions in the paper included: that during the construction of the embankment dam, the temperature condition in the foundation and embankment should be created close to that of the steady-state condition to avoid stability problems later; seepage cannot be permitted where frozen earth is used for a water barrier and structural stability; and studies of dam models are important for the solution of three-dimensional problems.

Comment: This is a good paper on the analysis of the thermal regimes of dams on permafrost. It presents isotherms for the cases analyzed.

Borisov, G.A. and G.Ia. Shamshura (1959) Experience in the planning, construction and use of earth dams at Noril'sk (in Russian). In Second Interdepartmental Conference on Cryopedology (Publication of the Academy of Sciences of the USSR, Moscow, 1956). Also in Materialy po Inzhenernomu Merzlotovedeniiu, p. 110-119. USA Cold Regions Research and Engineering Laboratory, Translation 26.

Five small (less than 10-m-high) earth dams on permafrost are described and the design concepts based on performance of the dams are discussed. Failures of two of the dams (one on the Kvadratnyy and one on stream 89) were the result of water finding or melting a "hole" through the embankment. The hole was then widened by heat from the seepage water. In these two cases no special provisions were made for freezing of the embankments to prevent seepage. A third earth dam was built on the Razvedochnyy Stream which froze to the bottom each winter. The dam showed no perceptible deformation over a period of four years, after which the dam was dismantled because it was no longer needed. Two earth dams (one on the Dolgaya River and one on the Naletnaya River) were successfully operated when provisions were made to keep their embankments and foundations frozen.

The following design features were pointed out: 1) earth dams in the frozen condition must be absolutely impervious, both in the embankment and the foundation; 2) refrigerating devices should be placed in the central parts of the dam cross sections; adequate distance should be provided; 3) provisions should be made for cooling the downstream slope in the winter and insulating it in the warmer season; 4) the upstream slope must be designed to allow for the expected settlement due to thaw consolidation; 5)

the crest of the dam must be wide enough to accommodate freezing units, 6) the downstream slope must be checked for stability prior to freezing and for creep of the seasonally thawing layer after freezing; 7) the downstream toe must be protected from the warming effect of the tailwater (berms may be used for this purpose); 8) the use of calcium chloride as a circulating brine at the dam on the River Dolgaya was not successful because there was poor heat exchange between the air and the brine at low air temperature, impurities in the brine deposited in the pipes and plugged some of them, and corrosion of the pipes caused leakage into the embankment. (The brine system was replaced with a forced air system and the dam operated successfully thereafter.)

Measured temperatures within the frozen dams on the Dolgaya and Naletnaya Rivers showed that the upstream slopes were unfrozen, refrigeration was required as a cutoff at the centerline of the dam, an insulating layer of sawdust on the upstream slope was not effective in preserving frozen conditions but a shelter over the downstream slope which could protect the slope from the sun and rain and yet permit the cold winter air to contact the soil proved to be quite effective. The downstream section of the dam on the Naletnaya River was cooled by constructing a shelter over the downstream slope to protect it from the sun and rain and to allow the cold winter air direct contact with the soil beneath the snow cover.

Conclusions of this paper: a) It is feasible to circulate air as a cooling medium to freeze the core of an earth dam, b) Calcium chloride was not as effective a coolant as air because impurities deposited and blocked the cooling pipe and leakage into the embankment dissolved the pore ice in the soil, c) Refrigeration of the dam from the downstream slope is possible only when snow is prevented from accumulating on the slope and when it is shaded from the sun in the summer, d) Earthen dams that require a frozen core must be refrigerated by circulating refrigerant in boreholes during construction and the temperature of the dam must be observed to check the effectiveness of the cooling system, e) Attempts to insulate the upstream slope with snow and sawdust during the summer are not advisable.

Comments: This paper describes valuable experiences but conclusions apply to dams in the Noril'sk area.

Bredyuk, G.P. and G.D. Mikhailov (1970) Effect of cryogenic processes on the strength of ground and stability of embankments during thawing. Borba s Naledami na Zheleznykh i Avtomobilnykh Dorogakh (USSR), Komitet po Zemlyanomu Polotnu, Vol. 9, p. 135-142. USA Cold Regions Research and Engineering Laboratory, Translation 318.

This article describes the settlement and weakening of a railroad embankment due to freezing and thawing of the soil. Frost action along the railroad embankment reduced the soil strength by 1.2 to 7 times its strength where no frost action occurred. Horizontal slippage of the thawed soil over the surface of the frozen soil was observed along the embankment during the thawing periods. Measurements of the thaw settlements due to the weight of the soil and the train loads are given in the paper.

Comment: This paper has application to frost action in embankments only. However, it is interesting to note the observation of the thawed soil slipping along the interface with the frozen soil.

Brown, W.G. and G.H. Johnston (1970) Dikes on permafrost: predicting thaw and settlement. Canadian Geotechnical Journal, 7(4) 365-371.

A method is developed for estimating the rates of thaw and settlement of dikes on permafrost using simple heat conduction and heat balance equations for a one-dimensional transient case. In developing an equation for the depth of thaw beneath a pervious dike it is assumed that the temperature of the seepage water through the dike will be the same as that of the reservoir, and thawing under the dike will proceed at about the same rate as thawing under the reservoir. The heat balance equation at the thawing front is assumed to be $Q_\ell = Q - (Q_1 + Q_2)$ where:

Q_ℓ = heat required to thaw the soil = Ldx

Q = heat conducted to the freezing front from the water interface = $k(T_w-32)dt/(x-s)$

Q_1 = heat to raise the temperature of the thawed soil = $C_u\ (T_w-32)dx/2$

Q_2 = heat removed when excess water is removed from the thawing front during consolidation = $62.4\ a\ (T_w-32)dx$

a = s/x = settlement/depth of thaw (estimated by observing the amount of excess ice in soil samples, taking into account the unfrozen water content).

By substituting the heat quantities into the heat balance equation, the depth of thaw (x) is determined. The calculated depth of thaw for the Kelsey dikes is in close agreement with the measured values. When the dike is impervious, the thaw penetration is influenced by water temperature on the upstream face and by the air temperature over the remainder of the dike surface. Thaw penetration vertically under the dike/water interface is about one-half that under the reservoir and slightly less in a horizontal direction. It should be noted that when thaw progresses laterally at unequal rates under the dike, large lateral differential settlements and cracking can occur. Thin, brittle cores can crack and the upstream slope can become unstable. A knowledge of the reservoir water temperature is important since the depth of thaw can be 30% in error if the water temperature is in error by 5°F.

Comment: This is a good paper. It should be noted that the heat balance equation does not include the heat required to raise the temperature of the frozen soil to 32°F.

Collins, C.M. and T.T. McFadden (1977) Investigation of slumping failure in an earth dam abutment at Kotzebue, Alaska. USA Cold Regions Research and Engineering Laboratory, Special Report 77-21.

The south abutment of the 6.1-m-high Kotzebue water supply embankment dam was instrumented with eleven strings of thermocouples to observe the changes in the thermal regime in this area where thermal degradation and bank sloughing were occurring. The 55-m-long dam is located on continuous permafrost which is estimated to be 73-m-thick with a temperature of about -2°C as measured at a depth of 10 m (measurements taken three months after installation). Results of the investigation suggested that the progressive advancement of the thaw surface into the abutment from the reservoir and the slumping of the abutment slope could eventually cause a breach of the dam. The recommendations for remedial action included: flattening the upstream slopes by adding nonfrost-susceptible soil to obtain a final slope of about 7 horizontal to 1 vertical; covering the final slope with riprap to reduce erosion from wave action; cleaning debris and removing unused facilities to reduce snow drifting; revegetating the area; lowering the reservoir in the winter; reducing, rerouting or providing insulated travelways for the traffic in the abutment area; and monitoring the thermal regime by reading the thermocouples twice a year (May and September).

Comment: This paper is a good summary of conditions that existed in 1976. It includes a table of temperature readings for about five (5) months only. The changes in the thermal regime cannot be evaluated until at least another year of temperatures are observed.

Davis, R.M. (1966) Design, construction, and performance data of utility systems, Thule Air Base. USA Cold Regions Research and Engineering Laboratory, Special Report 95.

The portion of the report covering the water supply system includes a description of the Crescent Lake Dam, the geology and climate of the area, and photographs of the dam and lake. Ice reaches thicknesses of 7 ft in the reservoir. The thickness of the ice increases from 0 in mid-September to 7 ft in late March and remains at 7 ft until June. Only 10% of the annual precipitation is available for water supply because of losses through evaporation in the summer, and transpiration and sublimation of almost all the snow in the spring. The dam has 5 ft of freeboard.

Comment: A cursory, general description of the dam and lake area is presented.

Demidov, A.N. (1973) Dam in the Vilyuy Hydraulic Power Station (in Russian). Trudy Gidroproekta, no. 34, p. 64-77. USA Cold Regions Research and Engineering Laboratory, Translation 526.

The article describes the construction of the 75-m-high, 600-m-long rockfill dam located on the Vilyuy River in Siberia. This is the highest dam of this type built in the USSR. The dam consists of a rockfill shell and an inclined, clay core protected by two-layer filters upstream and downstream of the core. The dam is founded on frozen bedrock. A concrete pad inclosing a 3.5- by 3.5-m grouting gallery forms a base for the impervious core. A single line of grout holes 15- to 20-m deep were grouted as

a final stage. Also, two rows of 4-m-deep holes were grouted to reinforce the blast-shattered rock and to reduce seepage beneath the concrete pad. Further grouting of the bedrock fissures is to be accomplished as the ice melts from the fissures. The requirement for further grouting will be indicated by the temperature sensors (thermistors) and the piezometers installed in the bedrock.

The rock for the rockfill was specified to have a strength of 600 kg/cm^2 after 50 cycles of freeze-thaw on the outer downstream slope and 150 cycles on the upstream section where the reservoir level fluctuates. The rockfill was placed in lifts 10-m to 15-m-thick and during the first summer 4 to 6 m^3 of water per m^3 was used to wash the rock into position. After the first summer water was not used because of the risk of filling the voids with ice, since it was discovered that subfreezing temperatures existed in the winter fill even during the ensuing warm period. The surface of each layer was therefore cleaned of contamination by bulldozers rather than water jets.

Soil for constructing the core in cold weather was stockpiled in the summer by mixing salt into the surface of the stockpiles to a depth of 2.5 m at a rate of about 18.5 kg of salt per m^3 of soil. Powdered industrial calcium chloride, mixed in the soil at the pits, reduced the depth of freezing of the stockpiles to 1.5 to 2.5 m. However, this frozen crust hampered the soil handling, so electrical heating was used to prevent overhanging frozen crusts and to allow the use of more of the stockpiled soil. It is stressed that the excavation, transportation and placement of the soil must be accomplished at a high rate in cold weather to avoid the formation of frozen clods, freezing the face of the excavation in the stockpiles, and freezing the soil on the embankment before it is leveled and compacted to the specified density. Although the core was constructed by the dry thawed method, soil was placed down to temperatures of -40°C. Soil placed at temperatures lower than -40°C had to be excavated and replaced. To obtain a good bond between successive layers of fill and uniform moisture content in the soil, sodium chloride or calcium chloride solution was spread on the surface of the previously placed fill layer before the next layer was placed. After the soil layer was leveled the surface was again treated with a salt solution.

To reduce heat loss from the soil in transit, the hot truck exhaust gases were circulated through the double bottom passage of the dump bed. In addition, airplane jet engines with gas temperatures up to 500°C were used to heat the surfaces of the fill and to clear ice and snow from the surface. Instrumentation in the dam included: electronic resistance thermometers and thermistors for temperature measurements; piezodynamometers for pore pressure measurements; and surface settlement marks and upheaval meters at the top of the core to measure frost heaving of the core. Vigorous air convection was observed in the rockfill. The rockfill has a temperature of -22°C and the core is completely thawed with a mean temperature of +2 to +3°C.

Comment: This paper presents many important details for the construction of embankment dams in cold regions. Information found here could be used profitably for future cold weather construction. It is clear that the dam was designed as a thawed dam on a rock foundation. The foundation grouting program and the excavation of soils for the core are related to the permafrost conditions; otherwise it's a thawed dam built in a cold environment. Heating in-situ frozen soil by jets must be uneconomical.

Echenfelder, G.V. and B.E. Russell (1950) Snare River Power Plant Project. Engineering Journal, Mar., p. 165-171.

This paper describes the construction of the hydroelectric project in general terms including the three earthfill dams. The largest dam is 63 ft high and 763 ft long and consists of a compacted clay core inside a pervious fine sand shell founded mainly on bedrock. This dam was constructed as an unfrozen structure. The clay for the core was excavated from a permafrost borrow pit by scraping successive layers of soil from the pit as it thawed under the action of the warm summer temperatures. To protect the core from frost during winter between construction seasons, a 5-ft-thick layer of sand was placed on top of the core. When the sand was removed the following spring, the maximum depth of frost penetration in the core material was found to be 15 in. (Common depths of frost penetration in this region are 8 to 9 ft.) One of the dams, located in a saddle underlain by 17 ft of permanently frozen muskeg and silt, was built 10 ft higher than required for water control to allow for anticipated settlement when the permafrost melted. The embankment settled 3 ft during construction. Further settlement after construction is unknown.

Comment: Many important details with regard to temperature, seepage, geometry of the site and dams, etc. are not given. Other than the fact that one dam was built on permafrost and allowed to settle due to foundation thawing, the paper is of little value for design information. The description of constructing a dam at a remote site in the north is quite informative.

Evdokimov, P.D., S.S. Bushkanets, G.M. Zadvarny and A.F. Vasiliev (1973) Studies of foundations and earth rockfill dams under severe climatic conditions. Seminar No. 2, Experience of Hydro Project Construction under Severe Climatic Conditions, Joint Soviet-Canadian Working Group for Co-operation in the Electrical Power Industry, Leningrad, p. 67-86.

This article describes embankment dams and their foundation materials constructed where below-freezing temperatures were involved. Projects described include: the Mamakan development, two dams of the Serebryanskaya hydroelectric project, the Iovskaya Hydroelectric Plant, the Verkhne-Iulomskaya Hydro Station, the Vilyuy Hydroelectric Plant, the Kolyma Hydroelectric Plant, and the water supply dam in the Irelyakh River near Mirnyy. The last three were founded on permafrost.

It is pointed out that two types of dams are most suitable for permafrost regions: dams that are founded on frozen soil that is subject to large subsidence upon thawing, where the greater part of the dam and foundation are preserved in a permanently frozen state; and dams built where the soil is not subject to large subsidence upon thawing, where natural and artificial thawing must be induced in the dam foundation during both its construction and operation. At this time, no concrete dams have been designed and constructed on permafrost soil in the USSR. However, if they were to be erected, the foundation strength would be determined by evaluating the internal friction and cohesion of the foundation permafrost soils. Strength and deformability parameters of frozen and thawed soils required for stability designs are: a) shear strength and adhesion, determined by direct shear tests (up to 50 kg/cm^2 vertical stress) and fall penetration tests; b) the forces of freezing and swelling; c) compressibility of both frozen and thawed soils, determined in odometers; and d) creep and long-term strength, determined by unconfined compression tests.

Comment: This article gives a good general description of some of the dams in the northern USSR along with diagrams of their cross sections. Design criteria are referenced as standards but not given in this paper.

Evdokimov, P.D. (1970) Design and construction of earth and rockfill dams in the USSR. In Transaction of the 10th International Congress on Large Dams, Montreal, Vol. 1, p. 137-149.

This paper describes the construction of embankment dams in the USSR in general terms and also describes nine specific dams. One of the dams referenced is the Vilyuy Dam which is described only briefly. In construction of embankment dams in the far north reference is made to the placement of material under water all year round. In the winter the water is heated and the water surface insulated. The dam for the Serebryanskaya Hydropower Plant located on the Kola Peninsula was reported to have been built by this method. Design criteria for construction of dams in permafrost regions are: for frozen soils that subside upon thawing, the dam and foundation are maintained frozen; for frozen soils where little subsidence will take place upon thawing, the foundation is allowed to thaw while the dam is in service.

Comment: The description of the Vilyuy Dam is quite brief. Much more detail can be obtained in other references listed.

Fulwider, C.W. (1973) Thermal regime in an arctic earthfill dam. In Permafrost: The North American Contribution to the Second International Conference, Yakutsk, p. 622-628. Washington, D.C.: National Academy of Sciences.

The Crescent Lake Dam is an earthfill water supply dam located near Thule, Greenland, where the mean annual temperature is -11.5°C. The final height of the embankment reaches about 18 ft above the original ground with a crest length of 1200 ft. The embankment consisted of pervious silty sandy gravel which froze back within two years after each placement of

fill. Temperatures were recorded in and beneath the dam to depths of 40 ft below the crest over a period of 6 years. Thermal disturbances were induced in the embankment because the crest was raised twice and fill was added at the toe during the observation period. Seepage was noted at the downstream toe near the end of the thaw period, but after the placement of the toe fill only minute seepage was noted near the end of the thaw season. The average annual freezing index was about (4510-4400) 4070°C. Isocurves in the cross section of the dam for the period May 1953 to August 1959 showed the top 3 ft thawed each year.

Comment: The paper gives detailed information on the thermal regime in a frozen earth dam that is not available elsewhere. The downstream slope of the embankment experiences greater thaw penetration than the upstream slope even though the impounded water maintained a temperature above 32°F beneath the ice in the freezing season. This increase in thawing on the downstream slope may result from the fact that this slope faces south and also the water content in the granular soil on this slope is low. A consequence of the downstream slope thaw is seepage through the seasonal thaw zone each year. Possible improved designs would be to increase the freeboard to at least the active layer depth or provide insulation at the crest or change the type of soil at the crest to reduce thaw penetration.

*Gapeev, S.I. (1967) Consolidation of the frozen soils of foundations by cooling (in Russian). Translated from Gidrotekhnicheskoe Stroitel' stvo. Hydrotechnical Construction, Dec., no. 12, p. 1082-1084.

The author proposes the use of self-adjusting automatic kerosene cooling devices to freeze embankment dams and their foundations in permafrost regions. The devices may be considered as gravity type single phase thermal pile tubes of different diameters (e.g. 5 and 7.5 cm), filled with kerosene, which draw heat from the earth in the winter by simple convection. The article describes cooling devices used on bridge piers. However, the author suggests that if these devices were used in the water supply dam on the Irelyakh River at Mirnyy instead of the forced-air cooling system the cost of operation of 10,000 rubles/year could be reduced to about 500 rubles every 10 years.

Comment: It is not clear if these cooling devices were ever used in dam construction.

Gevirts, G.Ya., V.L. Chelnokov and E.E. Khdoshoyants (1968) Construction of the underground structures of a hydroelectric station under perennial frost conditions. Hydrotechnical Construction, Nov., no. 11, p. 977-983.

The excavating, dewatering, and placing of the concrete lining intake tunnels and draft tubes for a power house in frozen rock are described in this paper. Excavation was by the usual drill, blast and muck operation. Water was encountered at one location and because of the negative rock temperatures and the low air temperature (-20°C) the dewatering system ceased to operate and water began to overflow and freeze. In the frozen

state the fissured rock was stable, but upon thawing, the rock had to be supported to insure stability. The concrete placed against frozen rock for the tunnel liner was protected from freezing by: 1) heating the rock to a depth of .1 to 1.0 m, 2) placing concrete at 1025°C and maintaining air temperature near that of the concrete, and 3) heating electrically by passing current through the freshly placed concrete. It was noted that steep temperature gradients (more than 20°C) through the thickness of the concrete can cause fissures. Therefore electrical heating can be recommended only in cases where there are two or three cooling surfaces. Temperature distributions in the concrete and rock were measured for each of the three previously described heating methods for periods up to 14 days. Temperature versus time for different depths of concrete and rock indicate the electrical method of heating to be less satisfactory for the tunnel liner constructed.

Gluskin, Yu.E., E.D. Losev, V.G. Petrov and N.V. Frumkin (1974) Kolyma Hydroelectric Station (in Russian). Translated from *Gidrotekhnicheskoe Stroitel'stvo*. *Hydrotechnical Construction*, Aug., no. 8, p. 722-727.

This rockfill dam with a central earth core is 126 m high and has a crest length of 750 m. It is founded on bedrock permafrost in the Kolyma River, Magadan, USSR. A concrete cutoff trench with a grouting gallery was installed beneath the core. The porous rock foundation is being hydraulically thawed before grouting. Thermal computations, considering seepage, indicate that the earth core will remain in the thawed state. The mean annual air temperature is -12°C. Continuous permafrost bedrock temperatures reach down to -8°C.

Comment: This article gives a general description of the hydroelectric project that was under construction at the time the article was written.

Gluskin, Yu.E. and V.Ye. Ziskovich (1973) Dam construction in the Northern USSR (in Russian). In *Permafrost: USSR Contribution to the Second International Conference, Yakutsk*. Washington, D.C.: National Academy of Sciences, 1978. USA Cold Regions Research and Engineering Laboratory, Translation 438.

Methods of constructing and operating earth and rockfill dams on permafrost are discussed. The following dams on permafrost were cited: the Vilyuy Hydroelectric Power Plant (74-m high), the Khantays Hydroelectric Plant (65-m high), and the Kolyma Hydroelectric Plant (124-m high). Foundation soils are classified according to ice content. High ice content soils must be maintained in a frozen condition to support a dam. Since the foundation beneath the upstream wedge of a dam which impounds a permanent reservoir will thaw it may be necessary to prethaw or excavate this part of the foundation where ice-rich permafrost is present. Prethawing is complicated, inefficient and time consuming. Methods for freezing portions of dams for seepage control include 1) freezing each layer of soil during construction, 2) freezing the core by artificial means before impounding water, 3) cooling the downstream slope in the winter during operation of the

dam by using wooden "vanes" to protect the slope from sun and to ventilate the ground surface beneath the snow cover.

The second method is used quite often for low and medium high dams, but for dams 25 m or higher it is suggested that freezing units be provided to refrigerate the foundation and to freeze the embankment. At sites where humidity is high and periods of warm weather occur frequently, the use of air as a coolant results in ice formation in the circulatory pipes with the possibility of plugging. Spillways and floodgates are quite vulnerable to thawing and deformation. Therefore the use of syphons and pumps for water passage may be advisable. To date there has been no experience with frozen cutoffs in the foundations of high head dams. Instead a grout curtain has been used. The downstream prisms of rockfill dams may develop ice in the pores due to penetration of precipitation and condensation of moisture from the convection of outside air through the pores. It is not clear if this ice formation affects the stability of the dam. To prevent the circulation of air from outside, a "mantle" of earth is placed on the downstream slope. The following recommendations and conclusions were presented in the paper:

1. Small impervious earth dams (less than 20-m high) constructed in the far north will freeze independently of design, method of construction or maintenance.

2. Ice forms in the pores of high rockfill dams.

3. The most vulnerable parts of earthen dams are the contacts between the dam and the outlet structure or spillway.

4. Existing freezing systems for creating frozen cutoffs in earthen dams are complicated and expensive to operate.

5. Better methods of placing rock fill in high dams in the far north are needed to reduce settlements.

6. The method of placing the impervious zone in dams at below freezing temperatures has significantly reduced construction time and has increased the effectiveness of the structure.

7. The search for economical, effective means for solving the seepage problems in dams and dam foundations on permafrost must continue.

Comment: This is a good brief summary paper of work in the USSR.

Grechishchev, S.E. and Iu.B. Sheshin (1973) Theoretical and experimental studies of thermal stresses and deformations of earth dams in winter (in Russian). Transactions of All-Union Scientific Research Institute of Hydrogeology and Engineering Geology, USSR Ministry of Geology, (unpublished MS), no. 55 (S.E. Grechishchev, Ed.), Moscow. USA Cold Regions Research and Engineering Laboratory, Translation [illegible]9.

This paper presents a theoretical method for calculating the thermal deformations of frozen earth dams and estimating the size of the transverse cracks that can occur due to thermal contraction. In addition, the size of the calculated crack is compared with that of a measured crack observed at adjacent spillways in a small earth dam in Yakutia. Using thermoelastic theory, the theoretical calculation takes into account the thermal deformation of the soil at different water contents and temperature distributions, insulation due to snow, and the cyclic air temperature.

The calculated width of the expansion crack was a little larger than the measured width but in good agreement.

Comment: This is a good paper and it brings out the important point that it is possible to estimate the size of transverse cracks in frozen embankments due to thermal contraction.

Gromov, A.I. (1968) Design and construction of hydraulic structures on permafrost. Transactions of Leningrad Hydroelectric Power Project, Planning-Surveying and Scientific Research Institute, no. 8, p. 165-175. USA Cold Regions Research and Engineering Laboratory, Translation 416.

The construction of the Mamakanskaya and the Vilyuyskaya Hydroelectric Stations (HES) is described in this paper.

Vilyuyskaya (HES) - This rockfill dam is 74-m high and 600-m long. It is founded on frozen bedrock at a site on the Vilyuy River where the mean annual temperature is -8°C. Construction operations continued through all seasons of the year. The rockfill placed in the summer was consolidated by water jets and that placed in the winter was located in the upper portion where there were no difficulties associated with the removal of ice.

The placement of the impervious zone in the winter when air temperatures reached -40°C was accomplished by maintaining the soil in a thawed condition through: stockpiling soil during warm seasons, introducing calcium chloride and sodium chloride to depths of 3 m (using 18.5 kg of salt/m^3 of soil), heating the upper layers of the stockpiles by elecrodes, and heating the bottoms of the hauling trucks. To avoid the formation of frozen layers of soil during placement, the surface was flooded with a solution of sodium chloride. During placement, all "large" frozen lumps were removed. A thick, two-layered filter was placed downstream of the impervious zone to prevent the movement of the soil when thawing of the impervious zone occurred.

Underground excavation of frozen rock was hampered in the warm weather by rock falls resulting from the thawing of the ice within the fissures.

The hydroelectric station at Mamakan (mean annual temperature -5.8 C) was constructed between 1956 and 1962. The dam is a concrete gravity type founded on frozen bedrock with a height of about 15 m. The concrete was placed in the cold weather in heated, insulated forms. In extremely cold

weather the concrete mixing water and aggregate were heated. Also, the new concrete was placed inside of heated tents. Rock surfaces and adjacent concrete were heated electrically or by steam to a depth of 1.5 m.

Comment: Both dams described in this paper are founded on bedrock and do not depend upon frozen conditions for stability or seepage control.

*Gupta, R.C., R.G. Marshall and D. Badke (1973) Instrumentation for dikes on permafrost: Kettle Generating Station. Canadian Geotechnical Journal, Aug., 10(3) 410-427.

This paper gives a brief general description of the design of the dikes for the Kettle Hydroelectric Plant and a detailed description of the settlement gages, surface marks, alignment points, slope indicators and piezometers that were installed in the dikes. The Kettle station is located 480 miles north of Winnipeg, Manitoba, near the town of Gillam on the Nelson River. Some of the saddle dikes are located on discontinuous ice-rich permafrost. The earthfill dikes have an average height of about 16 ft and were designed with a non-cohesive self-healing core as a defense against cracking, flat side-slopes, and sand drains in the foundation to assist in the dissipation of excess pore pressure during the thawing of the foundation. Also, foundation materials were excavated from the foundation so that the maximum settlement would be less than 5 ft. The purpose of the instrumentation is to: observe the behavior of the dikes during construction, reservoir impoundment and subsequent operations; define relationships between the rate of permafrost thawing and the rate of excess pore water dissipation; and obtain information for the design of future dikes in permafrost.

To measure vertical movements, spiral foot settlement gages were installed in boreholes at 0-ft, 5-ft and 10-ft depths below the foundation surface and marker pins consisting of 5-ft-long, 7/8-in.-diameter rods were driven into the embankment surface. Measurements of horizontal movement are made using alignment points consisting of a 3-in.-diameter pipe grouted into the embankment at a point 19 ft below the ground surface and protected by a 6-in.-diameter casing, and slope indicators in PVC casings. The movement of alignment points and settlement gages was measured by survey. Slope deformation gages were installed parallel to the upstream slope beneath bedding for the riprap. These gages consist of a series of horizontal-across arms embedded in the embankment slopes and attached to cables, under tension, which transmit slope movements through a system of pulleys to a vertical gage board.

Ground temperatures and depths of frozen soil are measured by thermocouples in vertical holes. The thermistors are located at 2-ft intervals to a depth of 2 ft below the foundation surface. To check the location of frozen soils, frost indicator tubes filled with methylene blue solution were installed. Pore water pressures are measured by air-operated piezometers where the ground is unfrozen.

After one year of operation, the instrumentation performed reasonably well; however, the following suggestions for improvement are given:

a. Slope deformation gages should utilize small diameter galvanized steel cables to transmit motion and the bottom cross-arms should be grouted into the foundation.

b. The plastic casing installed in the holes for the slope indicators should be replaced with aluminum or modified to avoid breakage at the joints, and the casing must be made watertight to avoid water entering the casing and freezing in the slope indicator tracks.

c. The Casagrande piezometers were blocked with ice where the water table extended into the active zone and attempts to use anti-freezing agents were unsuccessful because the specific gravity of the fluid varied in the standpipes or the solution was nonconductive.

d. The air-operated piezometers should be outfitted with porous plastic filters rather than a screen to avoid silt entering the piston area and restraining it. Also, to avoid ice formation inside the air pressure tubes, the piezometers should be pressurized with dry nitrogen gas.

Comment: This paper gives an excellent account of the installation of, and problems connected with installing different types of instrumentation in permafrost.

Johnston, G.H. (1969) Dikes on permafrost, Kelsey Generating Station, Manitoba. Canadian Geotechnical Journal, 6(2) 139-157.

Two dikes of the Kelsey generating station reservoir complex located on the Nelson River in Manitoba, Canada, and founded on discontinuous permafrost are described in considerable detail with respect to climate, foundation conditions, design considerations, and temperature and settle- ment measurements taken before and after the impoundment of water. The mean annual air temperature at the site has been 24.4°F for nine years and the average temperature of the permafrost was about 31°F. The foundation is predominantly varved clays extending to depths of 25 ft overlying a sand and sandy gravel deposit having a variable thickness up to 20 ft resting on top of bedrock. Islands of permafrost existed throughout the site to depths up to 35 ft. Extensive ice segregation existed in the varved clay.

The design concept was to allow the foundation to thaw and consolidate during operation of the reservoir. Sand drains were installed in the foundation to increase the rate of consolidation and, hence, to improve shear resistance and stability. Portions of the dikes were built 6 ft higher than required for reservoir operations to allow for settlement when the foundation thaws.

Ground temperature measurements taken by means of strings of thermocouples extending to depths of 20 ft showed warming temperature distributions and thaw depths increased each summer under the reservoir and beneath the dikes until eventually the soil remained thawed year round. Beneath the reservoir the soil remained unfrozen year round after one summer but in

one section of the dike three to five summers were required for continuous thawing. The mean annual surface temperature beneath the reservoir is about 42°F and the annual amplitude is about 30-35°F (i.e. from 32°F to 65°F). In the reservoir the rate of thawing within the top 10 ft is influenced directly by fluctuations in water temperature. Below 10 ft the influence of annual fluctuations in water temperature on the 32°F ground isotherm is essentially damped out. Temperatures in and under the dikes are affected not only by the reservoir water but also by the air temperature and water seepage though the dike and in the foundation. The variation in the thaw rate depends upon the local conditions. However, at this site, thawing during the initial 2 or 3 years under the dike and reservoir seems to be at a rate of about 5 to 6 ft per year "after which it proceeds at 2 to 3 ft per year, apparently decreasing with time."

Differential settlements of the surface occurred along the dike and at one time were as large as 5 ft. After the depressions were filled further settlement occurred and a maximum of nearly 7 ft was observed at the surface. Some longitudinal cracks were observed in the dike but no transverse cracking was observed. The rate of settlement followed a pattern similar to that observed for the rate of thaw. "The settlement and thaw rate patterns differ, however, in that while fluctuations in thaw rate are damped out fairly rapidly with increasing depth, changes in the rate of settlement during the year apparently continued each year in much the same manner for every depth." The total settlement of the dike surface located in permafrost can be attributed to:

a. Escape of the water from the thawing ice inclosures in the foundation.

b. Consolidation of the thawed soil in the foundation.

c. Consolidation of the dike sand fill.

Serious problems of foundation instability have not been experienced.

Comment: This is an excellent paper describing observations and experience in the operation of dikes on permafrost in sufficient detail to be of value for the design of future dikes.

Johnston, G.H. (1965) Permafrost studies at the Kelsey Hydroelectric Generating Station, research and instrumentation. Division of Building Research, National Research Council of Canada, Technical Paper No. 178.

This paper gives a general description of the embankment dams and dikes for the Kelsey hydroelectric station and details of the installed ground temperature and dike movement instrumentation. Two dikes are founded on ice rich varved clay which will be allowed to thaw after water is impounded in the reservoir. These two dikes, which reach a height of up to about 16 ft, were instrumented with thermocouples for ground temperature measurements to depths of 20 ft below the original surface; with frost

tubes; with auger-type settlement gages placed at about 5-ft elevation intervals to a maximum depth in the foundation of 20 ft; and with surface settlement gages. To determine the depth of thaw beneath the dikes, the reservoir, and an undisturbed control location, it was decided to measure temperatures rather than probe or use seismic or resistivity methods because of the ease of measuring temperatures and because seismic and resistivity surveys are not accurate enough.

Temperature measuring devices considered included: mercury bulb thermometers, resistance thermometers, thermistors, and thermocouples. Thermocouples were chosen for their durability, electrical stability, accuracy and ease of reading. In selecting the instrumentation for measuring dike movement the following factors were considered. Installations made during or prior to the construction of the dikes would be subject to damage or loss because of construction activities. It is difficult to install suitable instruments in permafrost. The equipment should be as simple as possible to minimize observer error. And because of the isolated location, maintenance and service requirements must be minimized. The types of settlement gages considered included: steel plates placed in the fill and on the original ground surface that could be located at various time intervals to determine their elevations; a telescopic type gage with a steel datum rod; earth auger-type anchors placed in the fill and in the frozen foundation at different depths; and steel rods with auger-type tips placed in separate drill holes. The latter gage was selected because it was the "most practical." Level surveys were made at regular intervals to determine the amount of settlement of the dike. Frost indicators consisting of 3/8 in. I.D. flexible clear plastic tubing filled with methylene blue solution were used to confirm the depth of the 32°F isotherm that was indicated by the thermocouple temperature measurements. The observational program for the Kelsey dikes included:

a. Meteorological observations of daily maximum and minimum air temperatures and precipitation (rain and snow), weekly measurement of snow depth and density, and weekly or semi-monthly measurement of ice thickness on the reservoir.

b. Dike settlement measurements are to be to the nearest 0.01 ft by a level survey every two weeks.

c. Ground temperature measurements and frost tube observations are to be made weekly at all locations.

Comment: This paper gives important details for instrumentation installation for ground temperature measurements and settlement observations.

Kamenskii, R.M. and I.P. Konstantinov (1975) Thermal regime of the reservoir of the Vilyuyskaya Hydroelectric Power Station and the permanently frozen ground of its bed. Moscow, Kolyma, no. 8, p. 30-33. USA Cold Regions Research and Engineering Laboratory, Translation 554.

Temperatures were measured at different depths in three locations along a line perpendicular to the shore in the reservoir and in the permafrost beneath the reservoir for the period 1969-1971. The temperature distribution within the reservoir water varies with location, depth, inflow, time of year and ice cover. The temperature data presented show: warm temperatures at greater depth in the spring when ice cover is present, almost uniform temperature near mid-June, and warmer temperatures near the surface in August. Temperature measurements in boreholes beneath the reservoir showed that the frozen rocks thawed to a depth of 7.75 m during a period of 2-5 years. The influence of the reservoir on the temperature of the permafrost reaches a depth up to 30 m.

This maximum depth was observed at a borehole on land near the shore of the reservoir. It is noted that during the winter there is a decrease in the depth of thawing when the water layers at the bottom are about 1.0-1.5°C. The observed average depth of thawing of the permafrost beneath the reservoir agrees quite well with the formula described by V.T. Balobayev.

Comment: This is one of the few papers that has measured temperature data for the permafrost beneath a reservoir and a comparison with predicted temperatures.

Kamenskii, R.M. (1973) Thermal regime of bearing ground and of the body of the Vilyuy Hydroelectric Power Plant (in Russian). In <u>Permafrost: USSR Contribution to the Second International Conference, Yakutsk</u>, p. 228-235. Washington, D.C: National Academy of Sciences, 1978. USA Cold Regions Research and Engineering Laboratory, Translation 438, p. 300-308.

The temperature regime in the rockfill dam and its foundation was measured by installing thermistor strings in boreholes along the profile beneath the clay core across the valley and at two selected cross sections of the embankment. The temperatures measured along the profile show a progressive thawing of the bedrock permafrost that supports the dam and also reflect an increase in temperature where seepage from the reservoir occurs. The temperatures in the cross sections of the dam indicated that the downstream toe and foundation of the embankment were becoming colder. The author suggests that temperature data can serve as an indirect index of the presence of water seepage through the dam since the temperature of the water from the reservoir is reflected in the temperature reading where seepage occurs.

This paper presents temperature data for the Vilyuy embankment and foundation for a period of about 4 years. Air circulation through the downstream rockfill section progressively reduced the temperature of the section and its foundation area near the downstream toe.

Comment: This is one of the few papers that contain measured temperature data for rockfill dams on permafrost.

Khukhlaev, G.A. (1969) Construction of a stone-earth dam of the polar Serebrianskaia Hydroelectric Plant (in Russian). Translated from Gidrotekhnicheskoe Stroitel'stvo, Aug., no. 8, p. 4-10. Hydrotechnical Construction, 1970, p. 690-696.

Information in this paper is essentially included in the paper, "Winter construction of dams at the Serebryanka-I Hydroelectric Plant," by Vasil'ev and Bukin (1975) in Hydrotechnical Construction, Jan., no. 1, p. 14-18. Cost data show that winter construction at this site cost 1.6 times as much as summer construction.

Comment: The puddle type of construction used at this site to continue work through the winter could have application in North America.

Kronik, Ya.A. (1973) Cryogenic phenomena in hydraulic structures built of earth (in Russian). In Permafrost: USSR Contribution to the Second International Conference, Yakutsk, p. 316-320. Washington, D.C.: National Academy of Sciences, 1978. USA Cold Regions Research and Engineering Laboratory, Translation 438, p. 240-243.

This report points out important problems concerning the construction of embankment dams in the north, including frost action, thermal deformation with crack formation, thermokarst, solifluction of embankments, natural and cut slopes, foundations, ice formation in the rockfill, frost weathering, and thermal erosion of waterways and reservoir shores.

During the construction of Khantay Dam the following phenomena were observed: mass ice formation due to emergence of water from the borrow pits and foundation excavations, thermokarst in the foundation areas and where electrical thawing was used, and frost heaving of the soil layers compacted in the core of the dam.

Kudryavtsev, V.A., L.S. Goragulya, K.A. Kontrat'yeva and V.G. Melemed (1974) Fundamentals of frost forecasting in geological engineering investigations. USA Cold Regions Research and Engineering Laboratory, Draft Translation 607, p. 456-477.

This textbook for an advanced course in "Procedure of Frost Investigation" includes not only frost penetration forecasting but also the predictions of change in frost conditions and frozen state resulting from all influences including man's activities. The thermal regime in embankment dams during construction are investigated as a unidimensional multifront Stefan-type problem with a hydraulic integrator. Thawing of a frozen embankment base due to water filtration through stratum through the foundation of a dam is computed as unidirectional thawing perpendicular to the stratum at several points along the seepage path. The Stefan equation is applied using a steady-state temperature distribution along the water-seepage path. This computation gives the first approximation of the thaw front at a given time. A second approximation of thawing front is obtained using the hydraulic integrator. The change in temperature of the flowing seepage water with time is computed at specified points along the seepage path by

taking into account the change in temperature of the adjacent thawed soils. Only two iterations are used because the known accuracy of the thermal properties of the soils does not justify additional iterations.

Comment: This is a comprehensive book on forecasting the freezing and thawing of frozen soil. The approximate methods presented on thawing due to seepage are adequate for simple geometry but for more complex geometry the hydraulic integrator is used (antilog device) and a digital computer is mentioned. Also, the method assumes that seepage occurs at a steady state initially.

Kulikov, Yu.G. (1968) Optimal height of a dam for preservation of bearing ground in a frozen state (in Russian). Transportnoe Stroitel'stvo, Oct., no. 10, p. 35-37. USA Cold Regions Research and Engineering Laboratory, Translation 451.

This paper presents equations and curves for determining the depth of seasonal thaw within and beneath an earth fill on permafrost. Ponding of water behind the fill is not considered, nor is groundwater considered. The equations are based on one-dimensional heat flow and Stefan's relationships for layered and homogeneous conditions. Two cases considered are: when the fill is placed in the thawed state and when it is placed in the frozen condition. A statistical study of railway embankments in Eastern Siberia showed that when the height of fill exceeds 2.5 to 3 m, thawing of the frozen foundation to a depth greater than the amount of seasonal thawing under natural conditions does not occur.

Comment: The title of this paper is misleading. The subject is seasonal frost penetration within and beneath earth fills. Water impoundment or seepage are not considered. Paper has a limited value for dams.

Kuperman, V.L. and L.N. Toropov (1975) Characteristics of the construction of hydraulic structures under severe climatic conditions. Translated from Gidrotekhnicheskoe Stroitel'stvo. Hydrotechnical Construction, Apr., no. 4, p. 7-9.

The experience in the USSR indicate that embankment dams, in general, are more economical to build in the far north than concrete dams. There is an advantage in placing powerhouse discharge facilities, etc., undergound since severe cold weather and snow have little effect on construction progress. The use of gouting and plastic membranes for water cutoffs and impervious zones of embankments are emphasized. Where the embankments or foundations are to remain frozen, the water discharge facilities such as spillways and conducts should not be located in or beneath the dam embankment since the heat from the flowing water during discharge periods can melt the frozen soils and cause excess seepage and unstable conditions.

Comment: This paper is rather general in nature but gives some specific suggestions for dam construction in the far north. Reliance on grouting and film membranes seems optimistic. No specific data is presented.

Kuznetsov, G.I. (1977) Evaluation of stability of an earth-fill dam based on strength of frozen zones of its profile. U.S. Army Cold Regions Research and Engineering Laboratory, Translation 628.

This paper outlines a method for analyzing the shearing resistance of frozen zones of embankment dams using simple statics. Two cases are considered: 1) A vertical frozen core along the axis of the dam where the required width of the core is determined to resist the hydrostatic pressure of the reservoir and the upstream embankment section by the sum of the simple shear at the base of the core and the weight of the core; 2) An inclined frozen zone along the downstream surface of the embankment whose uniform thickness must resist the full hydrostatic pressure from the reservoir by the sum of the weight of the zone and simple shear at both ends of the zone. The shear strengths used in the analyses are determined from SNIP (i.e. codes) for the type of soil and its temperature.

Comment: The simplified method outlined may be adequate for preliminary analyses but it gives no credit to the strength of the unfrozen soils in the embankment. The method apparently is used to determine if the frozen impervious barrier is in danger of fracturing from hydrostatic or earth pressures.

Lewin, J.D. (1948) Dams in permafrost. Public Works, May, Vol. 79, no. 5, p. 22-23, 32, Jun., Vol. 79, no. 6, p. 33-34, Jul., Vol. 79, no. 7, p. 57-58.

This paper is a series of three articles that suggest methods of design and construction of dams on permafrost. To determine the ice thickness on the reservoir the Stefan equation is suggested with modification to account for the insulating snow cover and heat from water flowing through the reservoir. The depth of thaw beneath the reservoir is estimated by balancing the amount of specific heat stored in the impounded water against the latent and specific heat of the frozen soil. By this method it is estimated that the depth of thaw is usually about 1/4 the depth of water in the reservoir. In addition to the stability criteria for dams in the temperate zone, dams founded on permafrost should fulfill other requirements. The dams should withstand differential settlement. There should be insulation to prevent heat from being conducted from the reservoir through the embankment. The permafrost should be insulated from the heat of the atmosphere. And the dams should be watertight. Types of dams suggested for use on permafrost soils included: timber (crib or beartrap), rockfill and earthfill dams. Emphasis is placed on earthfill dams designed with an impervious asphaltic-type membrane on the upstream slope protected from reservoir erosion by a concrete slab and thermally insulated against the cold air by the downstream gravel filter. With regard to spillways, the author suggests that they be located away from the main embankment. To reduce the amount of settlement, the foundation either should be maintained frozen or be thawed and consolidated prior to construction. Where the foundation is to be maintained frozen, the surface should be prepared when air tempera-

tures are below freezing if possible; otherwise, insulation must be provided to protect the permafrost until the embankment materials are placed.

Comment: This paper apparently is based on ideas, many of which have not been validated either by experiment or actual construction. Methods for estimating the thaw beneath the permafrost are crude and have been superseded by those that have been developed or refined since this paper was written.

Lyskanov, G.A. (1964) Experimental construction of a frozen-type dam in Yakutia, Yakutsk (in Russian). Yakutsoe Knizhnoye Izdatel'stvo. USA Cold Regions Research and Engineering Laboratory, Translation 479.

This paper briefly reviews experiences and problems in designing and constructing small embankment dams in the Far North; it describes a test embankment dam constructed on the Irelyakh River near Mirnyy in the USSR; it shows the change in the thermal regime within the test embankment for a period of about one year; and then gives recommendations for the design, construction and operation of small embankment dams on permafrost. The paper cites failures of small dams of the unfrozen type built on thaw-unstable permafrost, pointing out that frozen type dams are more suitable for thaw-unstable sites. The contact between the thawed soil and the frozen soil in the foundation of the dam is the weakest spot in the thawed type dam. The frozen type dam does not have this shortcoming but requires a permanently frozen zone in the dam. Experience in dam construction in the Far North indicates: the thawed type dam does not ensure stability; frozen type dams may require artificial cooling to maintain them watertight; and the use of natural cooling to freeze the body of the dam is possible.

A 6-m-high test dam founded on a high ice content silt, clay, gravel and disintegrated limestone (marl) permafrost was constructed near the town of Mirnyy for water supply. The impervious core was constructed of frozen soil in layers in the winter by saturating each layer with water and allowing it to freeze before the next layer of soil was placed upon it. The top of the core was thermally insulated by a 1.65-m-thick layer of compacted earth and a 0.1-m-thick layer of brush placed 0.3 to 0.5 m down from the top of the dam. In excavating for the spillway in the stream channel, the following measures were taken to avoid the development of talik: preliminary freezing of the existing talik; constructing a seepage cutoff; and providing for surface water drainage around the spillway area during construction. A wooden crib spillway, a rock-shale spillway and a rubble spillway were studied for the test embankment dam. Thermal insulation was used adjacent to the spillway, and "ridges" and waterproof membranes were created to reduce seepage and melting next to the spillway.

The isotherms based on measured temperature during the first year of operation of the dam showed pronounced cooling of the embankment from the top in December. Cooling continued in January, and by February the embankment temperature was less than -4°C. Until June a general cooling of the embankment continued from the top and bottom of the embankment. From July

to September there was a general rise in temperature of the dam and the foundation. And in October and November the temperature began to drop. Open shafts excavated in the top of the dam increased the cooling of the embankment markedly. It is recommended that the embankment be inspected periodically, noting specifically contacts between the spillway and embankment and frost cracks.

MacPherson, J.G., G.H. Watson and A. Kuropatnick (1970) Dikes on permafrost foundations in northern Manitoba. Canadian Geotechnical Journal, 7(4) 356-371.

Dikes were designed and constructed on discontinuous permafrost for a hydroelectric plant. The dikes on permafrost average 30 ft in height and have a maximum height of 50 ft. The foundations are primarily frozen silts and sands overlying dense till. The mean annual air temperature is 23°F with extremes from -50 to +90°F. Seasonal frost varies from 1 to 3 ft in the low-lying areas and 6 to 7 ft in the high ground. The design is to control seepage, to insure stability and to maintain sufficient freeboard to allow for settlement due to thawing of the permafrost. The stability analysis considered the thawing conditions. The temperature on the upstream slope due to water impoundment varies from 32°F to 70°F. Permeability is the most critical consideration with regard to excess pore pressure (stability) and seepage. Because the dikes were long and numerous neither complete removal of the permafrost nor refrigeration methods were considered economical. A combination of two approaches was used: vertical sand drains were installed, and the dikes were constructed with extra widths of non-cohesive, self-healing material which would allow differential movement and minor foundation failures without endangering stability. The embankment section consisted of semi-pervious homogeneous sections with gravel filters on the upstream and downstream slopes. The upstream slope is 1 to 4 and the downstream slope 1 to 3 with a 40-ft-wide roadway. Sand drains were installed on a 15-ft grid under the downstream slope, a 10-ft grid under the upstream portion and a 10-ft grid in the reservoir near the toe of the upstream slope. During design, the amount of permafrost to be excavated in order to limit thaw consolidations to 5 ft was estimated using the following equation:

$$\frac{V_w}{V_t} = \frac{5A}{HA} = \frac{G_s W - e}{(1+2.6W)}$$

$$H = \frac{5(1+2.6W)}{G_s W - e}$$

where

H = depth of high ice content soil layer
W = water content of soil (by wt.)
e = void ratio of soil
G_s = specific gravity

Curves for e = 0 and e = 0.3 were presented. If the heat study showed the thaw bulb would exceed H, then excavation would be required. The dikes were built sufficiently high so that after settlement adequate freeboard was still available.

Instrumentation consisted of settlement gages, marker pins (1-ft diam.), slope indicators, frost indicators, piezometers, thermocouples, and inclined settlement gages.

Comment: This paper presents a good description of the design and construction of dikes on permafrost. However, answers to the questions as to how the thermal degradation was estimated, and what are the consequences of installing sand drains in the reservoir near the upstream toe with regard to seepage and stability after thawing was complete were not clear. Performance data were not available to compare measured settlement with the estimated settlement.

Mel'nikov, P.I. and B.A. Olovin (1983) Permafrost zone dynamics in the area of the Vilyuy River hydroelectric scheme. In Permafrost: Fourth International Conference Proceedings, p. 838-842. National Academy of Sciences. Washington, D.C.: National Academy Press.

Fourteen years of temperature observations in and beneath the rockfill dam for the Vilyuy Hydroelectric Plant showed that the talik in the valley began freezing during and a few years immediately after construction. After the reservoir was filled, thawing of the frozen talik areas and the permafrost began across the valley along the axes of the dam. However, freezing continued near the downstream toe of the rockfill at the highest section of the dam i.e., in the former riverbed. This freezing is attributed to the convection of air through the pores of the rockfill. During the winter the cold air penetrates the downstream rockfill section cooling the rocks and contacting the relatively warm permafrost and/or seepage and tailwater moisture near the base of the dam. The heat and moisture acquired by the air causes it to rise, thus inducing convection in the downstream rock section. The moisture from seepage and convection deposit on the surfaces of the rock in the rockfill and partially fill the pores. Predictions of the thermal regime by models using conduction are incorrect. Evidently, it will take several decades to establish a steady-state thermal regime. Except for the downstream toe, the permafrost is degrading from 0.6 to 8 m per year. The foundation for this dam is bedrock, dolerite, that had an initial temperature of -9°C at locations away from influence of the river. Statistical analysis of the temperature observations from three boreholes in the flow zone for a 12-year period yielded empirical relationships between depth of thaw and time in the form:

$$\text{Depth of thaw} = C_1 \text{ and } C_2 \sqrt{\text{time}}$$

The paper also includes an equation for determining temperature at a depth of 20 m which accounts for: altitude, aspect and inclination of the ground surface.

Comment: This is one of the few papers that records the thermal regime of a rockfill dam for an extended period of time.

Moiseyev, I.S. (1959) Calculating temperature regime of earth dams in permafrost regions (in Russian). Moskovskii Inzhenerno-Stroitel'nyi Inst. Gidrotekhnicheskie Sooruzheniia, no. 29, p. 281-293, Moscow. USA Cold Regions Research and Engineering Laboratory, Translation 450.

The method of conformal representations is used for calculating the temperature distribution within frozen homogeneous earth dams (assumed to be shaped as a vertical wedge) on permafrost. The following three cases are considered: 1) reservoir temperature is constant and above freezing, air temperature is constant and below freezing, no geothermal heat; 2) air temperature is constant on both upstream and downstream slopes, no reservoir, and a cooling tube is buried along the longitudinal axis of the dam; 3) air temperature is constant, no reservoir, and geothermal heat is considered. Combinations of these three cases are formulated by superimposing thermal regimes.

Also included in the paper are computations for predicting the thaw line movement in the frozen earth dam due to heat from the reservoir and geothermal heat. Account is taken of latent heat of water in the computation.

Comment: The methods described are for simplified conditions and provide only a rough estimate for a real case. The methods do not take into account a non-homogeneous dam cross section, a roadway on top of an earth dam, the flow of ground water, the fact that dams are not infinitely high wedges, etc.

Mukhetdinov, N.A. (1973) Development of methods for calculation of the thermal regime of rock-fill dams in regions of severe climate. USA Cold Regions Research and Engineering Laboratory, Translation 616.

This thesis abstract presents the equations for heat conduction through the stones in the rockfill and the natural convection of air flowing through the voids of the fill. The equations are not derived but the terms are explained in detail. The solution of the equations is obtained by the finite-difference method using a digital computer. Quantitative relationships are established for: the surface area of the rockfill for a unit of fill volume; the mean characteristic diameter of the individual rocks; the aerodynamic resistance; and the thermal characteristics of the rockfill. The method is developed for calculation of the temperature fields of rockfill dams considering: the thermal and filtration anisotropy of the downstream rockfill zone; the heat exchange of the rockfill downstream slope exposed changing atmospheric temperatures; heat transfer of seepage water; nonlinearity of natural convection of air through voids of the rockfill. The system of equations for the determination of the temperature regime of the rockfill are given as:

$$C_{vol}(x,y)\frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x}\left[\lambda(x,y)\frac{\partial t}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda(x,y)\frac{\partial t}{\partial y}\right] + dv(x,y,t)(\theta - t); \qquad (1)$$

$$\frac{\partial \theta}{\partial \tau} + \frac{1}{\rho m}\frac{\partial \psi}{\partial y}\frac{\partial \theta}{\partial x} - \frac{1}{\rho m}\frac{\partial \psi}{\partial x}\frac{\partial \theta}{\partial y} = \frac{dv(x,y,\tau)}{C'_{vol}m}(t-\theta); \qquad (2)$$

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial \psi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial \psi}{\partial y}\right) = -\frac{\partial}{\partial x}(\gamma,\beta,m,\theta); \qquad (3)$$

$$\rho = \frac{\rho_0}{1+\beta\theta}. \qquad (4)$$

The boundary conditions are:

1. The temperature at the permeable surface of the downstream rockfill prism

$$\frac{\partial t_{sur}}{\partial \tau} = \frac{dv(x,y,\tau)}{C_{vol}}(\theta_{sur} - t_{sur}) + \frac{1}{C_{vol}}q, \qquad (5)$$

where $x = x_{sur}$
$y = y_{sur}$.

2. The temperature at the interfaces between the downstream rockfill prism and the other elements of the dam (central core, inclined core, foundation)

$$\lambda_k\frac{\partial t}{\partial n} = \lambda_{int}\frac{\partial t_{int}}{\partial n}; \quad t_{int} > t. \qquad (6)$$

3. The temperature of the moving air at the boundaries of the downstream prism

a)

$$\theta(x,y,\tau) = \theta(x'_{sur},y'_{sur},\tau) = t_{ext}$$

where $x = x'_{sur}$
$y = y'_{sur}$;

b)

$$\theta(x,y,\tau) = \theta(x_{int},y_{int},\tau) = t(x_{int},y_{int},\tau), \qquad (7)$$

where $x = x_{int}$
$y = y_{int}$.

4. The flow line function

a)

$$\psi = 0,$$

where $0 < x < B, y=0$ and $0 \leq y \leq H, x=0$

b)

$$\frac{\partial \psi}{\partial n} = 0, \tag{8}$$

where $x = x'_{sur}$; $y = y'_{sur}$;

c)

ψ = const.

in the air-impervious sectors of the downstream prism.

The initial conditions are:

$t(x,y,\tau) = t(x,y,0)$;

$t(x,y,\tau) = \theta(x,y,0)$;

$$\psi(x,y,\tau) = \psi(x,y,0) \tag{9}$$

where t, θ are the main integral temperature of the rockfill and of the air, °C;

t_{sur}, θ_{sur} are the same, at the pervious surface of the downstream prism, °C;

t_{ext} is the temperature of the external air, °C;

ψ is the flow function, m^2/hr;

dv is the volumetric heat exchange coefficient, $kcal/m^3$ hr °C;

α is the coefficient of volumetric expansion of the air, 1/°C;

ρ is the density of the air, kg/m^3;

ρ_0 is the density of the air at 0°C, kg/m^3,

γ is the volumetric weight of the air, kg/m^3;

m is the porosity of the fill;

C_{vol}, C'_{vol} is the volumetric heat capacity of the fill and air, $kcal/m^3$°C;

q is the quantity of heat carried into the dam by heat conductivity, $kcal/m^3$ hr;

λ_k $(\partial t/\partial n)$ is the heat flux from the downstream prism to the line of contact with elements of the dam, $kcal/m^2$ hr;

λ_{int} is the same, for the base, central core (inclined core), kcal/m hr °C;

n is a perpendicular to the surface, m;

x_{int}, y_{int} are the coordinates of the interface of the downstream rockfill prism with the base, central core (on inclined core), m;

x_{sur}, y_{sur} are the coordinates of the surface of the downstream prism, m;

x'_{sur}, y'_{sur} are the coordinates of the surface of a fictitious layer, m;

B is the width of the downstream prism at the base, m;

H is the height of the downstream prism, m.

Comment: This thesis is the bases of several papers by this author who is one of the few who have addressed this complicated problem analytically.

Mukhetdinov, N.A. (1969) Thermal regime of the downstream shoulder of rockfill dams (in Russian). Energiya, Leningrad, Vol. 90, p. 275-294. USA Cold Regions Research and Engineering Laboratory, Translation 586.

This paper presents the formulation and application of heat conduction and convection equations for computing the temperature distribution within the downstream rockfill zone of an embankment dam in cold regions. The conduction equations are developed and applied to the rockfill stones which are exposed to the temperature changes of the air flowing around them and the changes in the boundaries temperature (i.e. the downstream face, the foundation and the interface with the upstream impervious zone or core). The convection equations for the air are based on steady-state flow of air due to natural convection through the voids in the rockfill and the thermal expansion of the air. Factors considered in the equations include: pressure drops due to air friction against the rock surfaces; heat transfer between the air and rock surfaces; the porosity of the fill and the restriction of air flow due to impervious layers within the embankment or placed on the downstream surface of the embankment. The equations are solved using the finite difference method on a digital computer. The analytical results compare reasonably well with measured temperature observed for the Vilyuy Dam in Yakutia, USSR.

Comment: Aside from the ambiguity that arises from the translation from Russia, this is an excellent paper. It should be noted that the analyses do not take into account the change in phase of the water vapor to ice which has been observed in rockfill dams on permafrost.

Pikalevich, L.D. (1961) Frozen ground engineering-geologic investigations in connection with the construction of the Bratsk Power and Industrial Complex (in Russian). Moscow University. Merzlotnye Issledovaniia, Vol. 2, p. 189-197.

Frozen-ground engineering studies were made in 1956-1957 in the area of construction of the Bratsk (Angara River) Hydroelectric Dam to determine the natural soil temperature regime, depth of freezing, frost heaving and subsidence, and the effect of human activities on these factors. Six test areas of taiga, 15 to 20 m in radius were cleared of roots, stumps, and vegetation, models of wooden and concrete foundations were placed in them at depths of 1.2 to 3.5 m, and the effect of frost action was studied. A borehole 10-to 15-m-deep was drilled in the center of each test area, and the temperature regime, depth of freezing, and moisture content of the ground were measured. Additional measurement series were made in boreholes sunk in excavations, in connection with the problems that arise in foundation work in cold regions. Permafrost in the Bratsk area occurs in insular form, in low and protected places, so screens were erected adjacent to test areas to provide shade and simulate natural conditions. Water mains were laid in the same trench as the heating mains to avoid laying the water mains below the active layer (3.5 to 5.0 m). Calculations made with the IG-1 hydraulic integrator showed that frozen loam and sand-rubble material can be used in winter construction of earth dams, because this material will thaw out by the time the dam becomes operative in spring.

Comment: Methods rather than observational results are reported in this paper.

Plyat, S.H. and N.A. Mukhetdinov and Ye.A. Smirnov (1977) Thermal regime of earth rock dams constructed in the Far North. Soviet-American Working Seminar "Technology of Building Structures in Cold Climates", Moscow. USA Cold Regions Research and Engineering Laboratory, Translation 658.

This paper presents a method of calculating the temperature distribution within the downstream zone of a rockfill dam where air circulates through the fill by natural convection. The governing two-dimensional equations are based on conservation of energy, momentum and mass and the assumption that the coefficients can be determined experimentally. The equations presented are those developed by Mukhetdinov (1973) with slight modifications. Field observations of the thermal regime of the Vilyuysk Hydroelectric Power Station Dam showed that the maximum difference in the temperature between the calculated and the observed values was 4°C. The downstream rockfill was observed to have three temperature zones, namely: a lower zone (I) where the temperature remains below freezing continuously; an upper zone (II) near the top of the dam where the rockfill freezes and thaws during the year; and the area (zone III) immediately adjacent to the impervious core where the temperature remains unfrozen as a result of the heat supplied by the reservoir. In the cross section of the dam at its deepest point, zone I increased from 60% to 65% and zone III increased from 6% to 12% over a period of six years. During this period the rate of move-

ment of air in the rockfill fell by a factor of 2. Also at the end of this period the average annual temperature of the rockfill in contact with the foundation rock was -14.5°C. (Note that the mean annual temperature at the location of the dam is -8.6°C). Under the influence of this low temperature in the lower portion of the rockfill, the talik beneath the river bed froze to a depth of 54 m. Observations of the thawing of the bed and banks of the reservoir showed that there was practically no warming effect of the reservoir on the banks above the mean level of the backwater line. Below the water line, thawing occurred to depths of 9 to 11 m on the slopes of the reservoir and beneath the reservoir the greatest thaw depth observed was 50 m after 5 years of observations in 1975.

Comment: The details of the thermal analyses are not given. Mention is made of the influence of the change in phase of water vapor in the air that circulates by natural convection within the rockfill, but the equations presented do not reflect this factor. This paper summarizes the field observations better than most papers available from the USSR.

Rice, E.F. and O.W. Simoni (1963) The Hess Creek Dam. In <u>Permafrost: International Conference Proceedings</u>. National Research Council Publ. 1287, 1966, p. 436-439. Washington, D.C.: National Academy of Sciences.

This paper describes the design, construction and performance of the 24-m-high by 485-m-long embankment dam founded on permafrost and located near Livengood, Alaska where the mean annual temperature is about -4°C. The purpose of the dam was to supply water for hydraulic mining operations. The dam was initially designed as a hydraulic-fill, however because of the interruption of World War II, the hydraulic-fill construction was discontinued and the top 10 m of the embankment was placed as a compacted earth fill after the war. A sheet pile cutoff was installed in a steam-thawed trench beneath the central core of the dam. The trench and a portion of the gravel foundation area were refrozen by artificial refrigeration during and immediately after construction. During operation, the water from the reservoir was delivered to the mining area through a [illegible] which was subject to local caving especially at the portals. With continu[illegible] ous maintenance and by emptying the reservoir each winter, the dam per[illegible] formed satisfactorily until the mining operations ceased. However, [illegible] when the dam was not in use, the control gate of the drainage [illegible] the reservoir became stuck in the partially closed position and [illegible] voir did not completely drain. As a result the reservoir [illegible] the wooden spillway apron and eroded the earth channel be[illegible] causing the dam to be breached.

Comment: Thermocouple wires were severed during [illegible] upper portion of the dam and therefore no temperat[illegible] made in the embankment to determine the effe[illegible] ervoir each year in order to freeze the emb[illegible] tecting the permafrost at the outlet and s[illegible] by the observations made on this dam. For [illegible] Army Cold Regions Research and Enginee[illegible] by Kitze and Simoni (1972).

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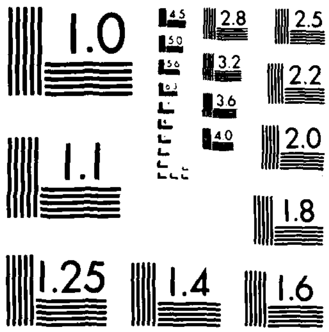

MICROCOPY RESOLUTION TEST CHART
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Savarenskii, F.P. (1950) Dams in permafrost regions (in Russian). Plotiny v raiona vechnoi merzloty. Izbrannye Sochenenlia, p. 370-371. Arctic Construction and Frost Effects Laboratory, Translation 29.

This paper describes problems associated with dams constructed on permafrost. Frost action in valleys can cause bedrock disintegration to depths up to 20 m (60 ft), requiring excavations and seepage cutoffs to extend to these depths. The heat from impounding of water in reservoirs thaws the foundations of dams and the reservoir areas, causing seepage, percolation and instability of the dams and the shores of the reservoirs. Dams subject to freezing were protected by an insulating blanket of peat. A dam 5-m high on the River Magdagach lost 90% of its water due to percolation because the concrete cutoff deformed and ruptured at high water level. A dam in Skovorodino 8-m high was constructed on 1 m of peat and 2.5 m of clayey gravel over compacted broken rock. The core extended to disintegrated bedrock. Original permafrost extended from 3 m below the surface to a depth of 90 m. The permafrost table receded 4 to 5 m and percolation beneath the dam endangered it.

Comment: This paper was so brief that essential information was omitted. One can only conclude that the dams failed due to thawing because of water percolation through them.

Semenov, N.G. (1967) Building dams in permafrost regions. Translated from Gidrotekhnicheskoe Stroitel'stvo, no. 9, p. 14-15. USA Cold Regions Research and Engineering Laboratory, Translation 452.

The construction of the water supply earth dam on permafrost on the Irelyakh River near Mirnyy is described. The dam has a maximum height of 20 m and a crest length of 320 m. Construction began in 1961 and ended in 1964. Permafrost extends to depths of 300 m (average air temperature 8.2°C) and at the site the foundation consists of a sandy silt having ice contents up to 60%. The dam has upstream slopes of 1 on 4 with two berms and a downstream slope of 1 on 3. Although the text states that since the dam is frozen no filters were required for seepage control, the figure showing the cross section of the dam indicates a layer of rockfill on the upstream and downstream slopes. The center section of the dam is cooled artificially by air circulated through vertical pipes (1.5 m on centers) extending through the embankment into the foundation along the axis of the dam.

The sequence and time of earth placement were carefully scheduled during the spring, summer and fall to avoid thawing the permafrost. Apparently all the soil was placed at temperatures above freezing, although some portions were placed at 0°C. The water contents of the soil were generally in the range of 12 to 18% but in the river channel 35% moisture content was permitted. Borrow soil had 40 to 45% moisture content and drying was accomplished in storage piles.

In construction, advantage was taken of the low temperatures during the winter to freeze the embankment as much as possible.

After construction, natural cold air was blown down the cooling pipes when air temperatures were below -15°C. The volume of cooling air is from 120 to 300 m^3/hr per column and from 11 to 22 m^2/hr per running meter. Observations of air temperature drops in the cooling system were made. A 12- to 15-m-wide frozen core was crested in about 3 winters.

Comment: This article is mostly descriptive and does not indicate methods of computing the freezing process, although the author states such computations were made.

Sereda, V.A. (1959) Experience in planning hydraulic structures with prolonged soil freezing (in Russian). Materials for Engineering Cryopedology, Seventh Interdepartmental Conference on Cryopedology, Moscow. Publication of the Academy of Sciences of the USSR, p. 120-128. USA Cold Regions Research and Engineering Laboratory, Translation 140.

This paper discusses the advantages of using artificial refrigeration systems to maintain frozen soil barriers against water seepage through embankment dams and harbor structures in cold regions. A properly installed refrigerated circulating brine system has advantages over a system that circulates cold air because: a) brine has better heat transfer characteristics, b) brine can be cooled more efficiently in warm weather if it becomes necessary, c) smaller pipes, etc,. can be used, d) air systems form form rust in the circulating pipes, e) ice plugs form in air systems. Data on the expenditure of effort required to maintain a mass of ground frozen indicated that the effort reduces with time, e.g. after 50 years the amount of effort required is about 10% of that initially required. Cost comparison between an earth dam with artificial refrigeration and a competitive design without refrigeration showed that the initial cost with refrigeration was less than without it but the operating cost was higher; therefore, for short periods of time, say 10 to 15 years, it is more economical to use refrigeration. Structures equipped with an artificial refrigeration system are more flexible with regard to temperatures during construction and operation.

Comment: This paper presents interesting ideas and theoretical analyses of cost but apparently no actual cost data from structures that have been built and operated.

Sheshin, Yu.b. (1973) Results obtained from investigating the mechanical properties and temperature expansion of frozen ground in connection with construction of earth dams in central Yakutia. Transactions, USSR Ministry of Geology, All-Union Scientific Research Institute of Hydrogeology and Engineering Geology (Unpublished), Moscow, no. 55, p. 86-91. (S.Ye. Grechishchev, Ed.) USA Cold Regions Research and Engineering Laboratory, Translation 449.

This paper briefly describes the apparatus for measuring the thermal expansion and contraction of frozen soil samples in the laboratory. The apparatus is constructed of materials with different thermal coefficients

arranged so that there is no need to make corrections for temperature changes in the apparatus. The results for a sand, two sandy loams and a loam are listed in two tables. One table gives the long-and short-term strengths and moduli for tension and compression tests at temperatures of -1°, -3° and -6°C and having water contents of 12, 15, 23 and 25%. The second table lists values of coefficients of thermal deformation of frozen soils for some soils, in the same general range of moisture contents but in a temperature range from 0° to -20°C.

Comment: This paper has valuable data, however the soil description is not precise.

Smirnov, E.A. and S.F. Vasiliev (1973) Design and construction of earth and rockfill dams under severe climatic conditions. Seminar No. 2, Experience of Hydro Project Construction under Severe Climatic Conditions, Leningrad, Joint Soviet-Canadian Working Group for Co-operation in the Electrical Power Industry, p. 87-108.

This paper presents a brief summary of requirements and problems in constructing frozen and thawed type dams on permafrost and describes in detail the construction of the embankments for the Irelyakh Dam (frozen type), Vilyuy Dams (thawed type) and Serebryanskaya Dam I (thawed type). A frozen-type dam is adopted in the case when the dam foundation is in ice-rich permafrost and the talik beneath the river bed is shallow. Soil placed in the embankment for this type of dam should a) be homogeneous in density and moisture content; b) contain enough moisture to fill the voids of the soil with ice in order to form a seepage barrier; c) contain plastic soil in the upper portion of the embankment, i.e. soil capable of withstanding slow deformation without cracking. The successful and economical construction of thawed dams with impervious cores in cold regions depends on efficient methods of placing clayey soils at low air temperatures. The basic problems in constructing clayey embankments year round are keeping the soil unfrozen until it is placed, and maintaining adequate plasticity until it is compacted. The method of depositing soils in water without compaction has found application in the Soviet north. The advantages of the method are: no drying or wetting of soil is required to obtain optimum moisture content; the amount of compaction equipment is reduced; and the construction season is extended since soil can be placed during rainy seasons.

The Irelyakh Dam is a 20.7-m-high embankment which was built in 1961-1964 to supply water to the town of Mirnyy. It is founded on fissured marl, limestone and sandstone with ice contents ranging from 26 to 43%, and soils with an average ice content of 50%. The central portion of the embankment consists of loamy soil which is maintained frozen by vertical cooling units spaced 1.5-m apart along the axis of the dam and extending down into the foundation. Each cooling unit consisted of two concentric steel pipes with diameters of 140 and 210 mm or 95 and 140 mm. In operation, cold air (below -15°C) is blown by fans and manifold down the annulus between the inner and outer pipes and returned upward through the inner pipe and discharged to the atmosphere. The difference in temperature of

the air entering the cooling system and leaving the inner pipe reached 10° to 15°C. During the initial start up period from January to May 1964, a frozen soil cylinder grew around each of the cooling units to form a 2-m-thick frozen wall.

The Vilyuy Dam located on the Vilyuy River (near the village of Chernyshevskiy) was built during 1963-1969 and consists of a rockfill embankment 74.5-m-high with an inclined clay core founded on permafrost bedrock. The mean annual air temperature is -8.1°C. Construction of the embankment was continued all year round, including work on the core at temperatures as low as -45°C. The construction techniques used for the core included:

1. Summer excavation of soil by bulldozers during progressive thawing of the soil, and drying to close to optimum moisture content.

2. Stocking the thawed soils in piles 16- to 18-m high.

3. Salting the top layers of stock piles to a depth of 2.5 m using 18-20 kg of calcium chloride per cubic meter of soil.

4. Electrically heating the soil around the working face of the stockpiles.

5. Hauling soil in truck beds heated with exhaust gases when ambient air temperatures were below -20°C.

6. Constructing the core in two longitudinal bands to avoid seepage paths along contacts between layers.

7. Reducing the placement working area when air temperatures were low.

8. Protecting the soil stored at the embankment with plastic sheets until the moment of spreading.

9. Spraying the soil placed in the embankment with a concentrated solution of sodium-chloride or calcium-chloride to ensure a reliable contact between successive soil layers.

10. Heating the fill surface to a depth of 2 to 3 cm with hot gases generated by an airplane jet engine.

11. Rolling the soil with loaded trucks to reach the design density in 6 to 8 passes.

The Serebryanskaya Dam I was built in 1966-70 on the Voronya River on the Kola Peninsula where the mean annual air temperature is about -1°C. The 78-m-high rockfill embankment features a massive core flanked by gravel transition zones and founded on granite bedrock. The core was constructed year round at temperatures as low as -38°C by using a puddling method, i.e. dumping the core material in pools of water retained on the working

surface of the core by longitudinal and transverse dikes. To prevent the puddling pools from freezing, sodium chloride was mixed in the soil at the borrow pit and on the surface of the fill prior to flooding. Also heated water was mixed with the river water in the pool. Placing a cubic meter of soil in the winter cost about 60% more than placing it in summer, but a sizable overall savings resulted from the reduction of construction time.

Comment: This paper is an excellent summary of the construction procedures used on three dams constructed in cold climates. It gives details of the soil and foundation conditions that existed at each site.

Thornton, D.E. (1974) Waste impounding embankments in permafrost regions: the oxidation pond embankment, Inuvik, N.W.T. Task Force on Northern Oil Development, Environmental-Social Committee, no. 74-10, p. 159-193.

An airstrip embankment which serves as a retaining structure for a sewage lagoon was instrumented with thermistors to determine the change in the thermal regime of the frozen embankment and the underlying permafrost that results from the impoundment. The embankment lies adjacent to the last channel of the Mackenzie Delta and is about 2.4 m high with 1.2 m of water behind it. The mean annual temperature and precipitation at this location are about -9°C and 28 cm. Five strings of thermistors were installed in a cross section to determine ground temperatures. Three strings of eight thermistors each were placed in boreholes to a depth of 12 m in the embankment and foundation. One string was laid in the upstream surface of the embankment and extended along the bottom of the lagoon. The fifth string of thermistors was inserted in a 60-m boring located downstream from the embankment. The temperatures were recorded weekly to the nearest 0.3°C.

Both undisturbed and disturbed soil samples were taken from the borings to classify the soils and determine their densities, water (or ice) contents and thermal properties for mathematical modeling. A simple explicit finite difference technique was used to solve numerically the partial differential time-independent heat conduction equation (Laplace's equations), i.e. the steady-state condition for a two-dimensional cross section of the embankment. It was assumed that the initial temperature of the soil was -4°C and that the boundary conditions were: air/ground interface temperature was -4°C, water/ground interface temperature was +3.5°C, the bottom and downstream side of the soil block considered in the analysis were -4°C, and the centerline of the lagoon (point of symmetry) adiabatic.

Also a closed-form solution was used for a semi-infinite homogeneous solid where the surface temperatures were -4°C on one half of the surface starting at the edge of the lagoon and +3.5°C for the other half of the exposed ground surface. A one-dimensional thaw calculation indicated that after two decades the soil beneath the center of the lagoon would thaw about 6 m. Temperature readings and boring data showed that a thawed zone existed in the lower portion of the gravel embankment and the underlying

upper surface of the silt foundation. Evidence of seepage through the embankment and the foundation was indicated by icings noted 150 m from the lagoon.

Comment: At the time this report was written only four months of temperature data were available, which is not enough to validate the mathematical models.

Trupak, N.G. (1970) Construction of earth dams on permafrost soils. Translated from Gidrotekhnicheskoe Stroitel'stvo, 40(9): 8-11. Hydrotechnical Construction, Sept., no. 9, p. 798-803.

Methods for establishing seepage cutoffs in dams on permafrost by means of artificial refrigeration systems are described using four dams built in the USSR as examples. It is emphasized that if permafrost is to be maintained in the foundation, water seepage must not be permitted at any section of the dam. The seepage cutoff may take different forms, such as clay or concrete cores, sheet piling, frozen zones or others. However, the cutoff extends the full length of the dam into the abutments.

A dam on the Kvadrat River failed within a few months after it was placed into service because ice inclusions thawed in the foundation and abutments. Both natural freezing from the downstream slope and artificial freezing have been used for seepage cutoffs. The artificial freezing involves refrigeration plants using ammonia or freon to cool a circulating brine or circulating cold air systems that operate in the winter only. The latter system is used where the mean annual air temperature does not exceed -5°C. In general, brine transfers heat from the soil at a higher rate than the air system.

A 10-m-high dam near the town of Norilsk consisting of a silty, clayey, sandy gravel was refrigerated using calcium-chloride as a brine which was cooled by winter air only. Shortcomings of the system were: a) poor heat transfer between the air and brine pipes because snow covered the pipes, b) untreated calcium chloride brine deposited impurities on the walls of the pipes, thereby reducing heat transfer (also in some cases the circulating pipes became completely plugged), c) partial freezing of the brine occurred in some freezing columns, d) poor fabrication resulted in leaks into the embankment, thus dissolving the ice from the soil. After four years of operation the brine was replaced with air. At first the air was forced into the system by fans but the fans warmed the air about 10°C. A vacuum system was then installed so that the fan heat was not added to the cooling air; however, snow was sucked into the system and caused blockages even with the intake protected by a grill.

An 11.5-m-high dam constructed in the Myaundzha River over a 12-m-deep talik contains a frozen soil seepage cutoff which is maintained frozen by an ammonia refrigeration unit in the critical section and by air circulated by fans in the remaining sections. Vertical shafts are spaced 1.5- and 12-m apart along the length of the dam. Pipes with diameters of 114 mm were installed in the shafts and air was sucked up the inner pipe at a velocity

of 20 to 22 m/sec and down the annular space at 8 m/sec. Roughly 200 cm of air passed through each freezing column per hour. With mean outside air temperature of -28°C and air discharge temperatures of -17°C the average rate of growth of the frozen soil column was about 2 mm per day for 192 days. Ice blockages occurred in the freezing columns during the summer until check and shutoff valves were installed on the system. Seepage through the fissured bedrock beneath the spillway endangered the dam for a period of time until the bedrock was grouted.

The 20-m-high water supply dam on the Ireyakh River was constructed with an air cooling system for the embankment and beneath the spillway. The embankment was maintained frozen by vertical cooling pipes but the fissured bedrock beneath the spillway was cooled by five horizontal freezing pipes with a diameter of 273 mm and a length of 50 m.

Freezing soil with air systems works best where the mean daily air temperatures are -15°C or lower for 15 October through 10 April.

Tsvid, A.A. (1961) Freezing of an earth dam from the dry slope side (in Russian). Vladivostok. Dal'nevostochnyi Nauchno-Issledovatel'skii Institut po Storitel'stvo. Sbornik Nauchnykh Rabot, Vol. 1, p. 93-104. USA Cold Regions Research and Engineering Laboratory, Translation 430.

This article discusses methods for increasing the rate of freezing earth dams by natural cooling of the downstream slope. Methods discussed include: a) removal of snow from the surfaces of the dam, b) covering the crest and downstream slope with insulation during the summer, c) installing a roof over the crest and downstream slope, and d) freezing an ice sheet on the downstream slope with ventilating tunnels for the circulation of cold winter air.

Methods of snow removal included constructing horizontal wind vanes to increase the wind velocity on the downstream slope and the usual mechanisms that are available, i.e. dozers, etc. The insulation of the downstream slope in the summer can be accomplished by the use of straw, temporary wooden panels or other insulation that can be removed in the winter. A suggested wooden roof over the downstream slope provides shelter from summer rains, shade from summer sun, and keeps the snow off the ground surface to promote greater frost penetration in the winter. At an installation of this type on a permafrost dam on the Namednaya River near Noril'sk the wooden covering was not waterproof and allowed rain to enter. Also snow partially plugged the space between the covering and the slope surface. Snow under the wooden covering in the summer can have a beneficial effect in maintaining the dam frozen, provided the snow thaws before the onset of the succeeding winter. A promising system for a permanent covering on the downstream slope is an ice sheet with ventilation tunnels and shafts. Such a system was used successfully on a dam near Noril'sk on the Dolgaya River. Isotherms based on measured temperatures showed the effectiveness of freezing this dam from the downstream slope. Equations and graphs of depth of freezing are presented in the paper.

Comment: This paper presents several interesting ideas and experiences with regard to freezing dams on permafrost from the downstream slope. The economics of the types of measures for freezing are not considered in the paper. The equations for freezing the dam were not derived; however, they are in the general form of the modified Berggren equation for one-dimensional freezing.

Tsytovich, N.A. and Ya.A. Kronik (1977) Cryopedological research in the construction of dams under severe climatic conditions. Collection of Works on Hydrotechnics and Hydroconstruction in Severe Climatic Conditions. Moscow: Nauka Publishing House, p. 11-23. USA Cold Regions Research and Engineering Laboratory, Translation 602.

This paper describes problems caused by frost action of soils placed in dams in the cold regions and frost susceptibility criteria. The problems considered are: frost action of soils that occurs during winter placement in the embankment; frost action at the crest of the embankment; frost action in the embankment, natural and artificial slopes; and frost action in the foundations of hydraulic structures. Frost action that occurs during the placement of soil reduces the density of the soil which in turn increases the permeability and reduces its strength along horizontal planes. This is a highly undesirable condition, especially in the impervious zone. It is pointed out that freezing can occur from below the layer if the lower soil layers were frozen at low temperature immediately after placement. Frost action at the crest can damage the roadway, besides increasing the permeability of the impervious zone and hence, increase the susceptible to seepage piping. Slopes that are susceptible to frost action will begin to move downward due to solifluction and thus upset the slope stability. The foundations of small hydraulic structures can be displaced or deformed by frost heaving and, in addition, seepage paths can develop where frost action occurs adjacent to or beneath the structure. Spillways are particularly susceptible to frost action since water flowing through the channel will thaw the abutting soil from time to time. The alternate freezing and thawing will loosen frost susceptible soil, thus inviting a seepage path to develop around the spillway structure. The criteria for determining frost susceptible soils is based on grain size, freezing conditions and moisture content prior to freezing. The tendency to heave is reduced in soils with silty clay size particles (less than 0.1 mm) and low moisture contents.

Soils classified roughly as 0.2% heave or less are practically nonheavable soils; 2 to 5% heave are slightly heavable soils; 5 to 10% heave are average heavable soils; and greater than 10% heave are extremely heavable soils. The latter soils are not recommended for use in dams in the far north. Slightly and average heavable soils are suitable for building dams when antiheave salinization is used on the layer interfaces during winter placement. Besides using salt to reduce soil heaving, normal pressure can be used to suppress heaving. At Vilyuy HES, pressures of 2.5 to 3 kg/cm^2 controlled frost heaving.

Comment: This is one of the few papers that consider frost heaving in the construction and operation of an embankment dam.

Tsytovich, N.A., N.V. Ukhova and S.B. Ukhov (1972) Prediction of the temperature stability of dams built of local materials on permafrost (in Russian with English table of contents). Leningrad: Stroiizdat, p. 143. USA Cold Regions Research and Engineering Laboratory, Translation 435.

This extensive review of dams built on permafrost summarizes the performance of embankment dams on permafrost, the general method of analyzing the thermal regimes of these dams, and some experimental studies of the temperature regime. Dams that have been constructed on permafrost are divided into three groups, namely 1) those that can be maintained frozen by natural environmental cooling, 2) those that require artificial cooling, and 3) those that are allowed to thaw. The latter group are essentially designed for the unfrozen condition by taking into account seepage control, settlement, and stability in the various thawing conditions. The two former groups depend upon the strength and deformation characteristics of frozen soil and the fact that no seepage can be permitted. A mixed design, where one portion of the dam is to exist in the thawed condition, e.g. spillway areas, and the embankment is to be frozen, is not recommended.

Methods for predicting the steady-state and transient thermal regime within a dam and its foundation utilized the thermal properties of the soil and assume that average constant temperatures exist at the boundaries. The hydraulic analog computer and the finite difference method are used for two-dimensional cases. The hydraulic analog is used for both the transient and steady-state cases while the finite difference method is used for the steady-state thermal regime only. Convection of pore water and seepage of water are considered in some of the predictions of thermal regime. One method given in detail uses the one-dimensional heat flow equations and the Stefan equation to analyze the thermal regime at various locations in the cross section of a dam. Using this technique the two-dimensional thermal regime is developed by drawing isotherms consistent with the one-dimensional analyses. Calculations for the thermal regime are given in examples.

Comment: This is an excellent summary work. However, it does not give the techniques that have been developed since about 1965. In the rockfill dam analysis, air convection is not considered. Isotherms based on measured temperatures are shown for some of the small dams. A comparison between the predicted thermal regimes and the measured ones is not made.

Vasil'ev, A.F. and Bukin, P.A. (1975) Winter construction of dams at the Serebrianka-I Hydroelectric Plant. Hydrotechnical Construction, no. 1, p. 22-28.

This paper describes the construction methods used for the 78-m-high rockfill dam on the Voronya River on the Kola Peninsula and the field and laboratory tests used to develop the method of placing fine-grained soil for the core of the dam in water at below freezing temperatures. Initially, it was planned to construct the fill by compaction methods at above

freezing temperatures. However, because of the short period each year that this method could be used to construct the core, it was decided to place the core material by the puddling method. This method consists of constructing dikes around the perimeter of the core area, creating a pond over the core surface, heating the water in the pond, insulating the surface of the pond with floating insulation (polystyrene), and dumping fill in the pond along the upstream and downstream edges of the core. The fill soil was sandy silt that segregated in the water to form a central zone of silt with sand zones adjacent to the upstream and downstream filters. The rockfill, filters (serves as external dikes for this core), and the core advance upward in lifts about 3 m high. Care was taken to avoid having frozen soil in the core by making borings in the core, and making analytical and laboratory investigations of the heat flow from the water to the soil. The time required to thaw a frozen layer of soil was calculated by using a one-dimensional equation based on constant pond water temperature, the specific heats and conductivities of the frozen and thawed soil, the latent heat of water, and a heat transfer coefficient between the soil and pond water. The time to thaw the soil calculated by the equation was much longer than the observed time because it did not account for heat flow to the bottom of the frozen layer or the water seepage that occurred. A laboratory experiment consisting of percolating +4°C water through the center of a frozen cylinder of soil confirmed the field observations that no frozen soil was left in the core.

To determine the effectiveness of the insulation floating on the pond, analytical and laboratory studies were conducted which took into account wind velocity up to 2 m/sec, the percentage of the pond surface covered with insulation, the water temperature and the air temperature and pressure. Using the equations developed from these studies, it was possible to determine the capacity of the heating equipment that would be required to prevent the core from freezing. By using the puddling method of construction year round, it was estimated that the construction period was reduced by two years with the construction equipment available. However, this construction procedure costs an additional 1.15 rubles/m^3 placed in the winter to cover the cost of insulation for the pond, fuel for heating, calcium chloride and special excavation equipment.

Comment: This dam was constructed in a permafrost region; however, the dam is built as an unfrozen embankment. The construction technique apparently was economical for the conditions that existed at this site. The method might be considered for construction in North America.

Zamolotchikova, S.A. (1968) Variation of geocryological conditions beneath dams depending on upper temperature limits (in Russian). Merzlotnye Issledovaniia, Vol. 8, p. 186-198. USA Cold Regions Research and Engineering Laboratory, Translation 457.

The location of the permafrost surfaces were determined for road (and railroad) fills, 12- to 15-m high, composed of "loams" by using an electro-integrator to solve the two-dimensional problem of heat flow with different temperatures at the boundaries. The following types of boundary tempera-

tures were considered: 1) the entire road fill and the adjacent ground surfaces are subject to freezing temperatures; 2) all surface temperatures are above freezing; 3) the road surface is held at below freezing temperatures while the side slopes of the fill and the surface of the adjacent natural ground are held at above freezing temperatures; 4) the side slopes of the fill are above freezing while the road surface and adjacent natural ground surface is held below freezing; 5) the surface of one side slope of the fill is above freezing and the remaining surfaces are below freezing; 6) the temperature of the surfaces of the fill and adjacent natural ground vary from below freezing to above freezing. Three figures show the computed location of the permafrost surfaces within and below the fill for different surface temperatures and surface conditions.

Comment: The title implies that dams or water impoundments are involved, which is not the case. Although the physical and thermal characteristics of the soils are listed and the final results are shown on the figures, it is not clear what fundamental relationships for heat flow were used. Apparently the steady-state heat flow equations were used. This study discusses permafrost but all the computations are for seasonal type freezing and thawing for non-permafrost conditions.

Zhdanov, V.A. (no date) Conditions of modeling heat and mass exchange processes in lower prism of rockfill dam in case of forced convection. Gor'kiy collection of works of the Gor'kiy Construction Research Institute, p. 37-42. USA Cold Regions Research and Engineering Laboratory, Translation 584, 1977.

This paper deals with the modeling of the downstream rockfill section of an embankment dam where the air is forced through the fill in the voids by the velocity of the wind striking the downstream surface of the dam. A method of modeling the heat transfer by air flow and vaporization is present using scaling factors to relate the various parameters in the heat-mass transfer equation between the model and the prototype. An undimensional approach is used. It is stated that air cannot be replaced by any other fluid in the model. Chips of rock from the dam with the same shape factor and porosity should be used in the model.

Comment: The equations presented are illegible in the copies that were reviewed.

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(List of Authors by Subjects)

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